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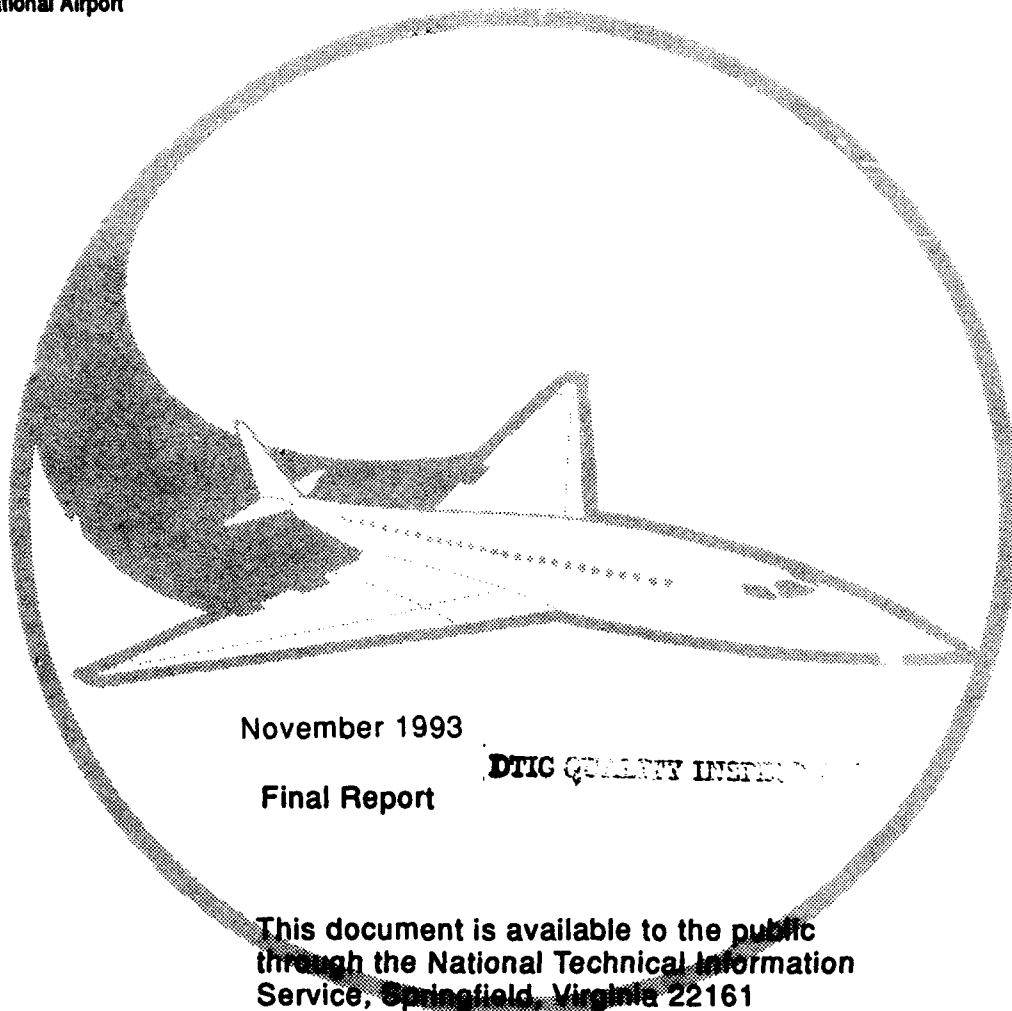
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FAA Technical Center
Atlantic City International Airport
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Pilot-Vehicle Interface



November 1993

Final Report

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16. Abstract The cockpits of the early transport aircraft were quite different from those produced today. Older cockpits contained numerous "steam gauge" style indicators. As technology advanced, these older electromechanical indicators were gradually replaced by newer, more reliable digital systems. Digital flight control and avionic systems are being used increasingly in modern aircraft. This trend yields cockpits of greater complexity and has swelled the amount of information with which the crew must deal. The way the pilot controls and monitors the state of the aircraft has also been greatly influenced by the increased use of digital systems. Additionally, new methods of aircraft system monitoring and control are being researched and implemented. These systems use new display technology, programmable display formats, voice input and output, and other new input and control devices. Systems and their cockpit interfaces were added as technological advances were made and new requirements generated. The human interface was given little consideration in the layout of the cockpit. Human qualities and failure modes were not taken into account in the cockpit design process. As the number of systems, components, indicators, and switches multiplied, the potential for error also grew. The emphasis of this report is on civil transport aircraft. This includes technologies such as displays, controls, and design methodologies, along with human factors concerns. The report consists of four sections: civil transport cockpit, cockpit standards, cockpit technology, and cockpit human factors. This report is to serve as a guide to Certification Engineers who are faced with the task of certification of new cockpit technologies.					
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EXECUTIVE SUMMARY

This technical report was initiated by the Federal Aviation Administration Technical Center's Directorate for Aircraft Safety, Flight Safety Research Branch. The purpose of the report is to provide in-depth coverage of the Pilot-Vehicle Interface (PVI). This report also forms the basis for chapter 19 of the Digital Systems Validation Handbook-Volume II. The Digital Systems Validation Handbook provides guidance to the certification specialists in new technologies. The report presents information in a way that enables the certification specialist to understand the information presented in type certification and supplemental type certification and to discuss these with the design engineer.

The report identifies issues dealing with the PVI and their impact on flight safety. It examines cockpit standards, technology, and human factors for commercial cockpits. Emphasis in this report is on civil transport aircraft, including technologies such as displays, controls, and design methodologies, along with human factors. There are four main sections:

- The civil transport cockpit
- Certification requirements and cockpit standards
- Cockpit technology
- Cockpit human factors

The civil transport cockpit section presents an introduction to cockpit technology. This covers the analog cockpit to the current "glass" cockpit. In Certification requirements and cockpit standards, relevant SAE documents are examined and summarized. Cockpit technology reviews various technologies used in the cockpit, including displays, keyboards, and voice. Cockpit human factors provides a review of the FAA's National Plan for Aviation Human Factors and examines the human factors aspects of cockpit technologies. In addition, a comprehensive bibliography is provided to serve as a basis for further research.

1. INTRODUCTION

1.1 Background

The cockpits of the early transport aircraft were quite different from those produced today. Older cockpits contained numerous "steam gauge" style indicators. These related to essential aircraft information such as altitude, airspeed, fuel, and various engine parameters. As technology advanced, these older electromechanical indicators were gradually replaced by newer, more reliable digital systems.

- Digital flight control and avionic systems have significant advantages, such as higher speed, less power consumption, reduced weight, lower volume, and lower cost when contrasted to older electromechanical systems. These systems are being used increasingly in modern aircraft. This trend yields cockpits of greater complexity and has swelled the amount of information with which the crew must deal. The way the pilot controls and monitors the state of the aircraft has also been greatly influenced by the increased use of digital systems.

Initially, each of these digital systems was a "stand-alone" component performing its intended function. Systems and their cockpit interfaces were added as technological advances were made and new requirements generated. The human interface was given little consideration in the layout of the cockpit. Human qualities and failure modes were not taken into account in the cockpit design process. As the number of systems, components, indicators, and switches multiplied, the potential for error also grew.

These stand-alone systems, along with their related indicators and switches, have now been implemented using digital technology. The use of this technology has opened the door for massive integration of the once stand-alone systems, through the use of data bus interconnections. Additionally, new methods of aircraft system monitoring and control are being researched and implemented. These systems use new display technology, programmable display formats, voice input and output, and other new input and control devices.

1.2 Scope

- The Pilot-Vehicle Interface (PVI) is the man-machine interface of the aircraft flight deck. PVI concerns itself with numerous technologies, especially when viewed from a military perspective. Some of the PVI-related technologies include configuration concepts, the pilot's associate, helmet systems, displays, controls, design methodology, escape systems, simulation, weapon system integration, supportability, and survivability.

Since the emphasis of this report is on civil transport aircraft, many of the military PVI technologies receive little or no consideration. The difference in mission dictates differences in technologies used. The emphasis for commercial transport cockpits includes technologies such as displays, controls, and design methodologies, along with concern for human factors.

This report consists of four sections:

- The civil transport cockpit,
- Certification requirements and cockpit standards,
- Cockpit technology, and
- Cockpit human factors.

Section 2 reviews various cockpits used in transport aircraft. Cockpits of current aircraft using analog indicators, digital cockpits, and the modern all glass cockpit are examined. Also covered are typical pilot requirements and tasks. This section is included for the reader's familiarization with cockpit activity and to help the reader understand the complexities of flying.

Federal Aviation Administration (FAA) Certification Engineers (CEs) are responsible for carrying out the certification process. The CE's job is becoming more complex due to rapid advancements in hardware and software technology. As a result, there are few specific certification procedures that cover the latest avionic technology. The CE must consult many sources for certification information. An appreciable number of standards and guidelines for PVI are developed by committees of the Engineering Society for Advancing Mobility Land Sea Air and Space (SAE). A comprehensive list of SAE documents pertaining to PVI along with a brief abstract on each is contained in section 3.

Section 4 examines various cockpit display and control technologies. A number of display technologies are examined, along with the construction and operation of these devices. Failure modes are identified and the relative advantages and disadvantages are addressed. Cockpit implementations of technologies, such as the Head-Up Display (HUD), also are examined.

Software concerns continue to increase along with the complexity of the digital flight control and avionic systems. Large volumes of software are now required for new aircraft, due to the extensive use of programmable digital logic. There are teams of software engineers assigned to maintain automated cockpits such as the one on the McDonnell-Douglas MD-11 (Aviation Week and Space Technology March 23, 1992). This report does not examine software influences on PVI. This is not to ignore the importance of software but since these issues are examined in detail elsewhere they will not be covered here.

There is a growing need to address the human factors aspects of cockpit technologies. It has been observed that many incidents and accidents can be attributed to human factors. Arbitrary and nonstandard arrangements of instruments, difficulty caused by instrument design, miscommunication in the cockpit and with Air Traffic Control (ATC), and insufficient training are among causes often cited in the chain of events leading to an incident or accident. Digital technology strives to eliminate many causal factors. However, some feel that the door has been opened for even greater errors to occur.

This report identifies issues dealing with the PVI and their impact on flight safety. This report was assembled using reviews of the literature, interviews with experts in the field, and reviews of accident and incident reports. It is to serve as a guide to CEs who are faced with the task of certification of new cockpit technologies.

2. THE FLIGHT DECK ENVIRONMENT

Cockpit complexity can range from very simple for general aviation aircraft to highly complex for the modern civil transport. This section provides fundamental information which is helpful for understanding this complexity by:

- Introducing the reader to some of the basic regulations that influence displays and instruments in the civil transport cockpit.
- Showing how these regulations were satisfied from older cockpit designs through newer ones.
- Introducing the reader to basic flight information and ATC procedures for the National Airspace System (NAS).

2.1 Cockpit Displays and Controls

There are many influences that shape cockpit design philosophy. New technology has replaced the cockpit full of electromechanical indicators with a few large Cathode Ray Tube (CRT) displays. Numerous switches controlling various systems have been integrated into Control Display Units (CDUs). The flight engineer's position has been eliminated and the functions performed by him integrated into captain and first officer duties. The human interface has also been the target of extensive research and consideration for cockpit design. Some of the other fundamental influences on cockpit equipment include reliability, power consumption, volume, weight, maintenance considerations, and cost.

These considerations have led to the development of a wide variety of input and output devices in the cockpit. Many devices are used in the cockpit to input information into the various aircraft systems. This information is used for communication, navigation, and other tasks required for flying. Following is a list of some input devices in current use or planned for use in the near future:

- Yoke,
- Rudder pedals,
- Side stick controller,
- Trackball,
- Capacitive touch pad,
- Keyboard,

- Discrete switches, push buttons, knobs, and levers, and
- Voice.

Cockpit output devices include:

- Printers,
- Alpha-numeric and graphic displays using CRTs and Liquid Crystal (LC),
- Discrete indicators and lamps,
- Shaker sticks, and
- Aural annunciators such as tones and voice.

2.1.1 Cockpit Regulations

Regulations and standards influence not only what appears in the cockpit, but also its arrangement. Requirements for the certification of aircraft are contained in the Federal Aviation Regulations (FARs). Many sections of FAR Part 25 specify what equipment is required on transport category aircraft and where the equipment is to be placed.

Section 1303 presents the requirements for flight and navigation instruments. Basic instruments such as a temperature indicator, clock, and magnetic compass must be installed and be visible from each pilot station. In addition, other instruments must be included such as:

- An airspeed indicator,
- An altimeter indicator,
- A vertical speed indicator,
- A gyroscopic rate-of-turn indicator,
- A gyroscopic bank and pitch indicator, and
- A gyroscopic direction indicator.

These six indicators are important to navigation. Their location in the cockpit is also specified in section 1321:

The flight instruments required by § 25.1303 must be grouped on the instrument panel and centered as nearly as practicable about the vertical plane of the pilot's forward vision. In addition-

- (1) The instrument that most effectively indicates attitude must be on the panel in the top center position;
- (2) The instrument that most effectively indicates airspeed must be adjacent to and directly to the left of the instrument in the top center position;
- (3) The instrument that most effectively indicates altitude must be adjacent to and directly to the right of the instrument in the top center position; and
- (4) The instrument that most effectively indicates direction of flight must be adjacent to and directly below the instrument in the top center position.

This arrangement of flight displays describes a "T" configuration which is found in the older analog cockpits such as the Boeing 727 or McDonnell-Douglas DC-9. In the modern glass cockpits, such as the McDonnell-Douglas MD-11, these functions have been integrated into one display called the Primary Flight Display (PFD). Figure 2.1-1 shows the basic layout of information for the PFD.

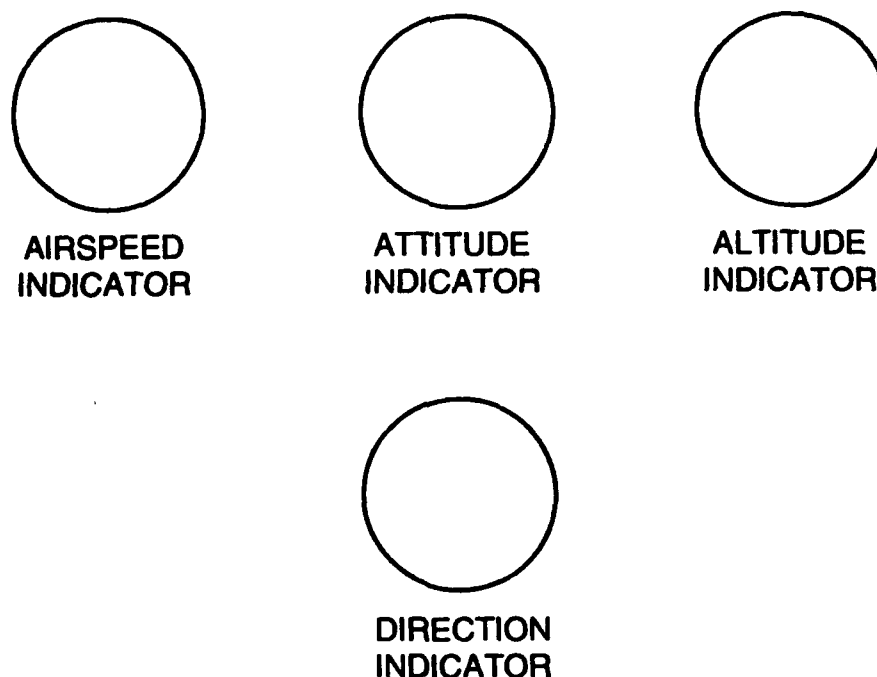


FIGURE 2.1-1. PRIMARY FLIGHT DISPLAY LAYOUT

Note that although there is freedom to configure the display presentation in infinite ways, the same basic T configuration is maintained as when individual indicators are used. The attitude is in the center of the display. Airspeed is adjacent to and directly to the left of the attitude display. Altitude is adjacent to and directly to the right of the attitude display. The heading is adjacent to and directly below the attitude display.

Standardization of the PVI is not only driven by the FARs, but also by recognized standards such as the SAE ARP4102/7, "Electronic Displays". Appendix A of this Aerospace Recommended Practice (ARP) covers symbology location for the PFD as shown in figure 2.1-2.

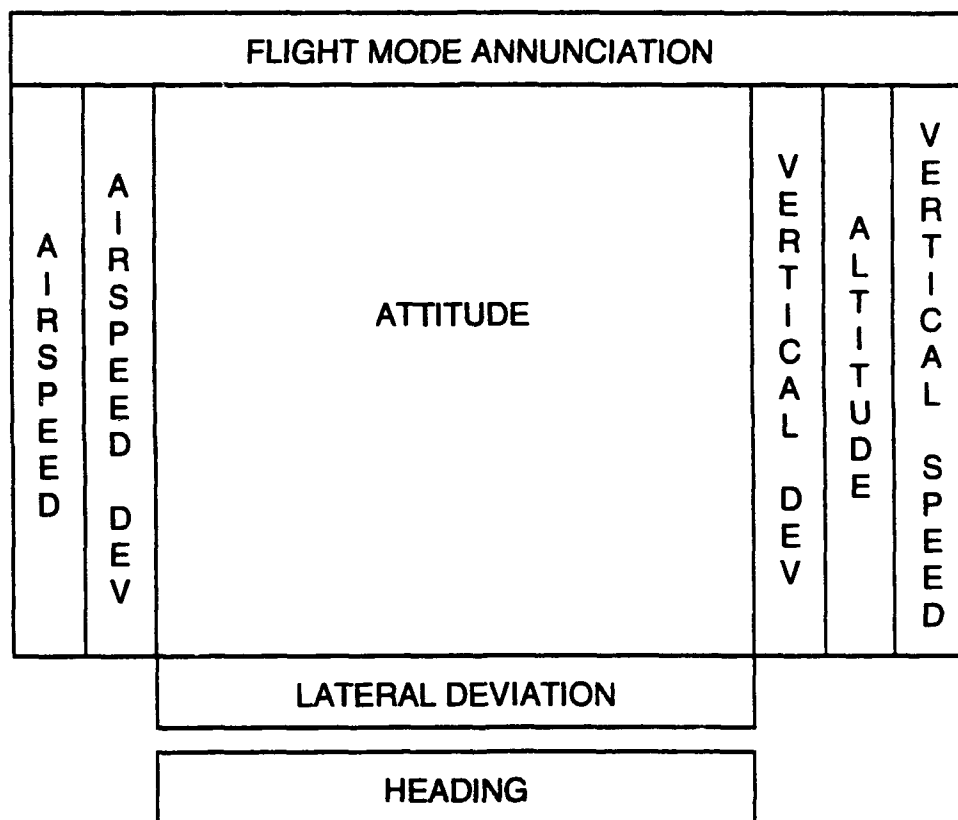


FIGURE 2.1-2. SYMBOLOGY LOCATION DIAGRAM

Requirements for other important indicators, such as those used to monitor the powerplant, are also presented in the FARs. SAE ARP4102 further recommends the arrangement of the indicators or displays by function and by the physical powerplant location. An easily identifiable and logical arrangement of the displays and indicators is highly desirable. For instance, for these displays, a top to bottom or left to right arrangement should be followed for:

- Primary power or thrust parameter indicators,

- Primary limitation and function indicators, and
- Secondary limitation and function indicators.

Recommended layouts of other displays and controls also are found in the SAE ARP4102.

Regulations regarding instrument lighting are given in FAR Part 25, Section 1381 to ensure the readability of all cockpit devices. The prescribed color scheme for warning, caution, and advisory lights is specified. Numerous other systems and their requirements are delineated.

Section 1309 specifies that all aircraft equipment and systems be required to function properly under all foreseeable operating conditions. The FAA has designated three levels of functions: flight-critical; flight-essential; and flight-nonessential.

- Flight-critical systems are designed so that the occurrence of any failure condition which would prevent the continued safe flight and landing of the airplane is extremely improbable.
- Flight-essential systems are designed so that the occurrence of any other failure conditions which would reduce the capability of the airplane or the ability of the crew to cope with adverse operating conditions is improbable.
- Flight-nonessential systems are those systems whose failure could not significantly degrade aircraft capability or crew ability.

In order to meet the FAR requirements for failure conditions, designers implement redundant systems and displays. For instance, if one PFD fails, another is available in front of the other crew member. If both of these fail, then separate indicators, which provide the same flight information as the failed devices, may be used.

The influence of technology on cockpit design is seen by comparing the older and newer cockpits. Older analog cockpits are full of discrete electromechanical indicators, each representing a separate system or parameter. When digital systems were introduced into the cockpit, many of the indicators and switches were replaced by digital displays, CRTs, and keyboards. Modern integrated cockpits are now manufactured with large CRTs completely spanning the instrument panel and several Multifunction Control Display Units (MCDUs) mounted in the pedestal.

Older aircraft often are refurbished by manufacturers to extend the operating life of the aircraft. The cockpit is frequently the focus of major changes during this time. For instance, the Boeing 747 had 971 lights, gauges, and switches on the earlier models. This number was reduced to 365 on the Boeing 747-400 model in part by using MCDUs and 6 large CRTs.

2.1.2 The Analog Cockpit

Figure 2.1-3 shows the Boeing 727 cockpit which is an example of the analog cockpit. There are over 40 indicators and numerous switches, status lamps, and buttons just on the front panel. In addition, there is a third crew member's panel with further rows of indicators, switches, buttons, and status lamps. The basic "T" configuration of the primary flight displays can be seen directly in front of the flight crew on each side of the cockpit. The displays consist of:

- Horizontal Situation Indicator (HSI),
- Flight Director Indicator (FDI),
- Airspeed Indicator, and
- Altitude Indicator.

The engine status indicators are located in the center panel along with the landing gear interface and other discrete annunciators and indicators. Analog cockpits, in general, have a cluttered appearance, requiring more eye movement and time spent by the crew with eyes focused in the cockpit. An additional difficulty occurs when new systems are added to the existing aircraft. Finding space in the cockpit for indicators is a major problem.

2.1.3 The Digital Cockpit

The McDonnell-Douglas MD-80 is an example of a digital cockpit and is shown in figure 2.1-4. The front panel consists of a mixture of CRTs, digital displays, electromechanical indicators, and other discrete lights and switches. A "T" configuration of discrete primary flight displays is used, with the horizontal situation and attitude, along with other parameters, being displayed on separate CRTs. This combination is called the Electronic Flight Instrument System (EFIS). Airspeed and altitude are displayed on the electromechanical indicators to the left and right of the EFIS.

Other digital displays are used in the McDonnell-Douglas MD-80 such as those for the flight director system mounted on the glare shield. The engine and fuel status indicators also use discrete digital displays for each monitored parameter. With the digital cockpit, MCDUs with integral CRT displays became the preferred manner of systems control for new designs.

Much of the clutter associated with the analog cockpit has been removed in the digital cockpit. The McDonnell-Douglas MD-80 has 492 switches, gauges, and lights compared to 833 on the earlier McDonnell-Douglas DC-10 (Bekemeyer and Shannon 1986).



FIGURE 2.1-3. BOEING 727 COCKPIT

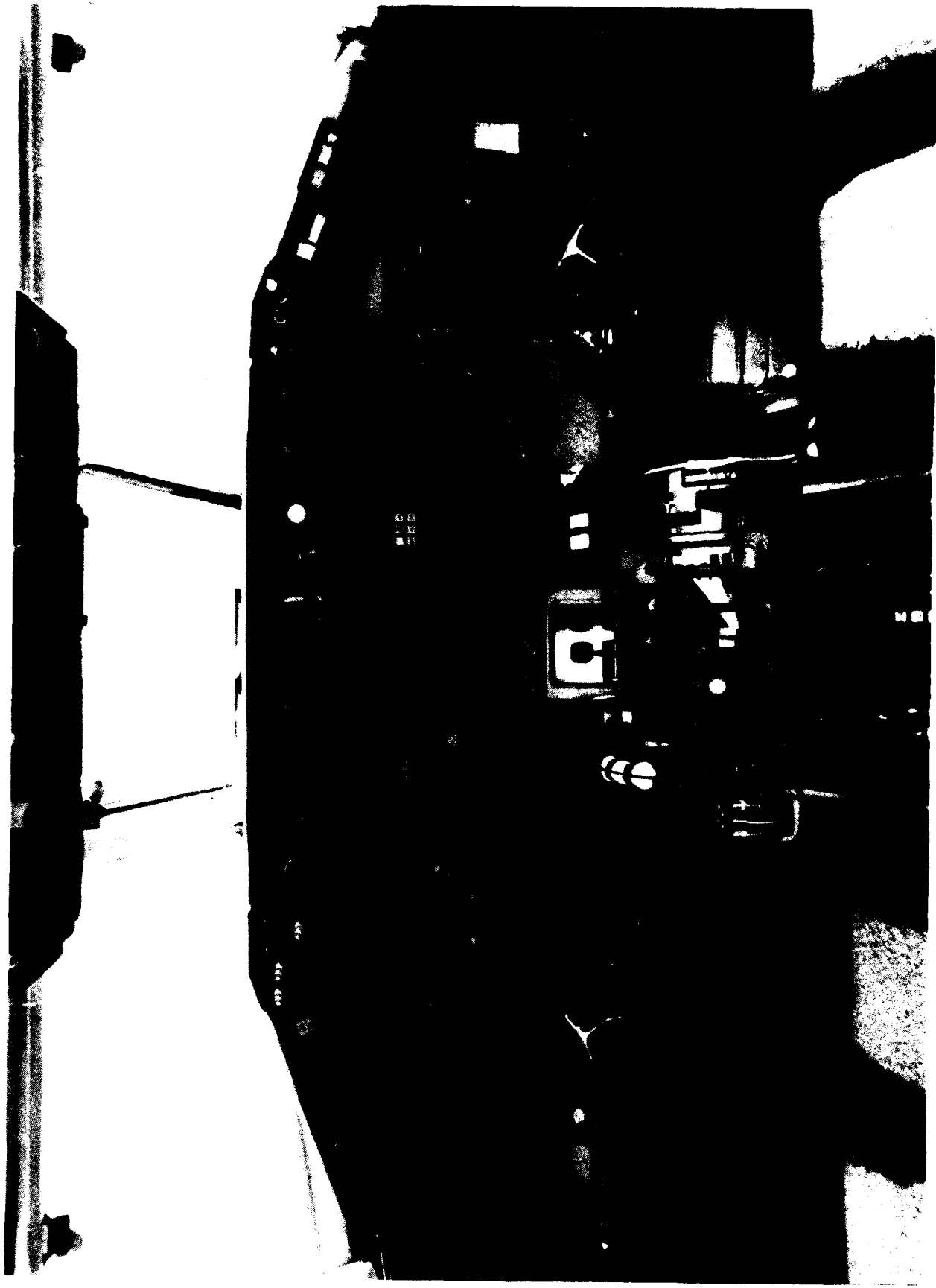


FIGURE 2.1-4. MCDONNELL-DOUGLAS MD-80 COCKPIT

2.1.4 The Integrated Cockpit

The McDonnell-Douglas MD-11 is an example of an integrated cockpit and is shown in figure 2.1-5. The front panel consists primarily of six large (8 inch x 8 inch) color CRTs across the panel along with the landing gear interface. The CRTs are used to display the primary flight data, navigation data, and engine and systems data. There are three pedestal mounted MCDUs. Two MCDUs are dedicated to the Flight Management System (FMS) and the third is used for maintenance functions. Flight director controls are located on the glareshield.

The McDonnell-Douglas DC-10, predecessor of the McDonnell-Douglas MD-11, had a total of 833 switches, gauges, and lights as compared to 362 on the McDonnell-Douglas MD-11. There also was a 75 percent reduction in the Line Replaceable Unit (LRU) count due to digital integration (Bekemeyer and Shannon 1986). In addition, the crew size was reduced from three on the McDonnell-Douglas DC-10 to two on the McDonnell-Douglas MD-11. This was accomplished by automating the functions formerly performed by the flight engineer.

Functions of the flight guidance and control systems were initially stand-alone implementations on aircraft such as the Boeing 727. In modern automated aircraft, such as the McDonnell-Douglas MD-11, many functions of the flight guidance and control systems are integrated into the Flight Control Computer (FCC). These systems include (Bekemeyer and Shannon 1986):

- Autopilot,
- Flight director,
- Yaw damper,
- Longitudinal stability augmentation,
- Pitch trim,
- Autothrottle, and
- Stall warning.

The cockpit has a clean, uncluttered appearance because of the integration of many systems into a common CRT display. The problem of clutter, however, has not been eliminated. Individual displays can become cluttered with extraneous information. Careful consideration should be given to the information requirements of particular tasks and the format of presented data.



FIGURE 2.1-5. MCDONNELL-DOUGLAS MD-11 COCKPIT

2.2 Pilot Tasks and Vehicle Interaction

There are many tasks that pilots are required to perform. A primary responsibility of the pilot is stated in the Airman's Information Manual, Section 5-71b:

The pilot in command of an aircraft is directly responsible for, and is the final authority as to the safe operation of that aircraft.

Carrying out this duty is no small task. The attention of the flight crew may be focused in many different directions including:

- Discussing plans and activity with other crew members,
- Monitoring aircraft systems,
- Monitoring outside the cockpit,
- Communicating with ATC, and
- Programming and other aircraft control activities.

Communication among crew members is necessary so that each is aware of any action or planned action by the other member. Crew members must constantly monitor the state of the aircraft to ensure its safe operation. In addition, the environment outside the cockpit must also be constantly scanned for other air traffic in order to maintain safe separation.

ATC communication involves procedures for departure, en route, and arrival. This activity, by itself, can keep the flight crew very busy. Some of the typical departure procedures are:

- Contact clearance delivery and advise destination or direction.
- Monitor Automatic Terminal Information Service (ATIS) for routine airport advisories.
- Contact ground control for clearance to taxi to the active runway.
- Contact clearance delivery for departure heading, altitude, transponder code, and frequency.

Some of the En Route Procedures are:

- Maintain communications with ATC.
- Change frequency when requested.

- Report position to ATC when required or requested.
- Maintain assigned routes.
- Maintain prescribed holding patterns when required.

Some of the ATC Related Arrival Procedures are:

- Contact approach control.
- Listen for traffic advisories and safety alerts.
- Acknowledge receipt and respond to ATC approach clearance.
- Follow procedures for the chosen approach.

The interface to automated systems is performed by the MCDU. Since there has been an increasing trend towards automation, more time is now required of the flight crew in keyboard programming. Keyboard proficiency and accuracy have become major safety concerns.

2.3 Aircraft System and Equipment Implementations

Many systems that exist in transport aircraft require an output device as well as a method of input. Some systems use CRTs dedicated to that particular system, while other systems share a common, multifunctional display device. The SAE ARP4102/7 recommends criteria for displays associated with various cockpit systems. The identified displays include:

- PFD,
- Navigation Display (ND),
- Flight Management Display for FMS,
- System Display (SD), and
- Alerting Display (AD).

Systems requiring a flight crew interface will be developed continually due to changing technologies and the overriding concern for flight safety. How information is presented on the flight deck is a major concern and is the focus of considerable research. One such study (Pomykacz 1991) identifies displays that airline operators intend to use for the Data Link system. Likewise, if an Enhanced Vision System (EVS) or Microwave Landing System (MLS) becomes a requirement in the future, similar studies will be necessary.

Some systems may require a dedicated CRT while other systems such as Data Link may share use of an existing display device. An advantage of digital display systems is that they are easily made multifunctional. When a new system requires a display interface, it is easily accommodated due to the wealth of programmable devices existing in the modern transport cockpit. What is not always obvious, however, is when, where, and what to display.

3. CERTIFICATION REGULATIONS AND GUIDELINES

3.1 Certification and Regulations

Certification is the process of obtaining FAA approval for the design, manufacture, and/or sale of a part, subsystem, system, or aircraft, by demonstrating that it complies with all applicable government regulations (Elwell, et al. 1991). The requirements for the certification of flight deck systems are covered in the FARs. FAR Part 25 Sections 1303, 1309, 1321, and 1322 contain regulations related to PVI.

FAR 25.1303, "Flight and Navigation Instruments," calls for each pilot station to have an airspeed indicator, altimeter, rate-of-climb indicator, bank-and-pitch indicator, rate-of-turn indicator, and direction indicator (non-stabilized magnetic compass). In addition, a free air temperature indicator, a clock, and a direction indicator (gyroscopically stabilized, magnetic, or nonmagnetic) must be visible from each pilot station. FAR 25.1321, "Arrangement and Visibility," specifies the flight deck instrument installation, arrangement, and visibility. This section establishes the basic instrument "T". FAR 25.1322, "Warning, Caution and Advisory Lights," defines the color code for warning, caution, and advisory lights. FAR 25.1309, "Equipment, Systems, and Installations," requires that systems and equipment be designed to perform their intended functions under any foreseeable operating conditions.

In order to assist the equipment manufacturer in meeting the requirements of certain FAR sections, the FAA publishes documents known as Advisory Circulars (ACs). The ACs specify various methods to comply with the FARs. AC 25-11 entitled "Transport Category Airplane Electronic Display Systems" provides direction for the certification of CRT displays that are used by pilots for guidance control or decision making. It contains general certification considerations; color, symbology, coding, clutter, dimensionality, and attention getting requirements; display visual characteristics; failure modes; information display and formatting; and integrated display and mode considerations.

Technical Standard Orders (TSOs) are other documents or standards published by the FAA. TSOs outline the minimum performance standards a part must meet. They are used by manufacturers for equipment or part production approval. The TSOs reference documents such as the FARs and other industry standards. A more in-depth discussion of the certification process and the relationship among regulatory documents can be found in Elwell, et al. 1991.

3.2 Pilot-Vehicle Interface Guidelines Developed by SAE Committees

The SAE is a world-wide organization of over 60,000 members representing different engineering disciplines. These members come from civil, mechanical, electrical, chemical, and metallurgical engineering, academic, and scientific backgrounds. The SAE Technical Standards Board is responsible for managing and operating the SAE standards development program known as the Cooperative Engineering Program. This program serves industry, government, and the public by developing standards used for design, manufacture, testing, quality control, and procurement.

The Technical Standards Board defines the work to be accomplished via the Cooperative Engineering Program. In order to do this, the Board oversees four councils and five divisions. One of these councils, the Aerospace Council, is the world's largest producer of non-government Aerospace Standards (ASs). This council is made up of executives from the same air and space community that the SAE standards program serves. The SAE standards and specifications are drafted by industry experts and used voluntarily by industry and government. These industry experts make up groups known as SAE Committees that develop SAE ASs. These standards are used extensively by the Department of Defense (DoD) and the FAA.

There are many SAE Committees that address diverse aerospace-related subjects. SAE Committees that perform activities related to PVI include:

- G-10 Aerospace Behavioral Engineering Technology (ABET),
- A-4 Aircraft Instruments, and
- S-7 Flight Deck and Handling Qualities Standards for Transport Aircraft.

The duty of the G-10 Committee is to define recommendations that could provide cost-effective and efficient operation of an aircraft/machine. The A-4 Committee is responsible for mechanical, electromechanical, and electronic cockpit instrumentation standards that apply to all civil aircraft. This committee emphasizes minimum performance standards that are expected to be referenced in FAA TSOs. The scope of the S-7 Committee is to develop standards to be used by flight deck design engineers for instrumentation, controls, vision, environment, comfort, workload, displays, and aircraft handling qualities.

Three types of documents are covered in this section, ASs, Aerospace Information Reports (AIRs), and ARPs.

ASs contain:

- Design standards that are in accordance with proven aerospace engineering practices;
- Parts standards that conform to engineering practices in propulsion, propeller, accessory equipment, or airline industries;
- Minimum performance standards that are referenced in FAA TSOs; and
- Other specifications that do not fit in the Aerospace Material Specifications (AMSs) or ARPs.

AIRs provide basic engineering data or information useful in the aerospace industry for reference or guidance. ARPs furnish dimensional, design, or performance recommendations that are intended as guides toward standard engineering practice.

The following sections provide summaries of PVI-related documents developed by the three SAE Committees. All documents contain references to reports pertinent to the subject being reviewed and most contain a glossary of key terms. It is important to note that these summaries are intended to give the reader the general nature of the document. If more detailed information is needed, it is recommended that the reader obtain the appropriate SAE document.

3.3 G-10 Committee - Aerospace Behavioral Engineering Technology

3.3.1 ARP4155 - Human Interface Design Methodology for Integrated Display Symbology

3.3.1.1 Scope

This document provides an approach to designing symbology for integrated displays. This approach stresses the relationship among symbols, the information they encode, the context in which the symbols are displayed, and the tasks these symbols support.

3.3.1.2 Background

In developing integrated display symbology, the designer must ensure that display symbols:

- Convey the information they encode,
- Remain effective when used in combination with related symbols, thus enabling the user to achieve a prescribed level of performance, and
- Do not interfere with the interpretation of other flight deck symbols as well as the performance of other flight deck tasks.

As the amount of information in flight decks increases and display devices become more flexible, the ability to satisfy the above requirements diminishes without some type of compromise. In order to produce an effective display, the designer must implement a structured design approach early in the development cycle.

One way to produce an effective display is to use consistent symbol-task pairings. This facilitates pilot training as pilots operate different subsystems in one aircraft or transition from one aircraft type to another. As flight decks become more integrated and increasingly complex, symbol consistency becomes more difficult to maintain. Other factors that contribute to the difficulty in symbol consistency include changes in flight deck configuration throughout the operating life of an aircraft, improvements in technology, and changes in regulatory, airline, and ATC requirements.

3.3.1.3 Design Methodology

The recommended steps for display symbology design are defined through the use of a flowchart. The process is divided into four phases: requirements, development, evaluation, and operation. Each step within each phase has an associated approach along with one or more reasons why the step is necessary. This is followed by a brief explanation of the key elements involved in completing the step.

As an example, the first step in the process is recognizing a new or modified task. As part of the approach, "the designer should clearly identify the task and related performance objectives the desired symbology is meant to support" (ARP4155 1990). There are two reasons why this step is necessary:

- To improve the chances that the proper task has been recognized, and
- To determine the criteria against which the chosen symbology will be evaluated.

The factors that result in a new or modified task are listed as key elements involved in completing this step (e.g. transfer of information from one display medium to another one). The designer is cautioned that the task performance requirements must be as objective as possible since they will be used as performance evaluation criteria later in the process.

The type of information presented in the above example is given for every step in the display symbology design flowchart.

3.4 A-4 Committee - Aircraft Instruments

3.4.1 AS8034 - Minimum Performance Standard for Airborne Multipurpose Electronic Displays

3.4.1.1 Scope

This standard specifies minimum performance standards for airborne multipurpose displays, including head-down, head-up, monochromatic, and color displays. Three display types are covered:

- Type I: Flight and Navigation Displays,
- Type II: Engine Systems and Warning Displays, and
- Type III: Control Displays.

Multipurpose displays can include one or more of the following components:

- Symbol Generator/Processor Unit,

- Control Panel, and
- Display Unit.

This ARP illustrates a sample interconnection configuration among these components.

3.4.1.2 Standards

Standards covered in this document are organized as:

- General Standards,
- Minimum Performance Standards Under Standard Conditions,
- Minimum Performance Standards Under Environmental Conditions, and
- Test Procedures.

3.4.2 ARP1874 - Design Objectives for CRT Displays for Part 25 (Transport) Aircraft

3.4.2.1 Scope

This SAE document contains information that is related to SAE document AS8034 (described above). It recommends performance criteria for direct view CRT instrumentation on the flight deck of FAR Part 25 aircraft. ARP1874 covers general requirements for CRT displays such as equipment functions, environmental conditions, implosion protection, and malfunction indications.

3.4.2.2 Detail Requirements

The detail requirements include the CRT's physical characteristics, photo-colormetric characteristics, and operating time. As part of physical characteristics, this ARP recommends useful screen size, viewing characteristics, etc. Photo-colormetric characteristics include luminance, color, and the color difference between symbols and between symbols and background. The operating time of CRT displays includes warm-up time, lag time, and time for data updating. Warm-up time is specified to be less than one minute from initial turn-on. At this point, the CRT will display usable and accurate information. The lag time between the selection of a format on the CRT and the actual display of the data on-screen should not exceed one second. The lag-time between selection of flight/mode data and actual display should not be more than 1/4 of a second. Other lag time requirements are found in ARP1068B "Flight Deck Instrumentation, Display Criteria and Associated Controls for Transport Aircraft." The rate for data update is specified at a minimum of 15 Hertz (Hz).

The remaining portion of ARP1874 presents the definition of key display terms.

3.4.3 AIR1093 - Numeral, Letter, and Symbol Dimensions for Aircraft Instrument Displays

3.4.3.1 Introduction

There are many factors that determine the readability of instrument dial characters. This makes the task of establishing a concise set of rules for all situations in an aircraft very difficult to accomplish. Where there is a great amount of space on the aircraft instrument for the placement of characters, size is not an issue. In most cases, however, the designer is not given a large amount space for letters or symbols. The designer must therefore work with a small amount of space for these items while concurrently providing a high level of legibility.

3.4.3.2 Purpose, Environment, and Requirements

This AIR recommends the minimum character and symbol dimensions for use in aircraft instrument dials and panel displays. These recommendations are specified for viewing distance; marking requirements such as minimum character brightness, brightness contrast between characters and background; and the color of illumination.

The numeral, letter, and dial requirements specify the color of characters, symbols, and background; the dimensions for characters on flat dials and counters; the spacing for characters and words; and the suggested styles for both letters and symbols.

3.5 S-7 Committee - Flight Deck Handling Qualities Standards for Transport Aircraft

3.5.1 ARP4101 - Flight Deck Layout and Facilities

3.5.1.1 Scope

This document provides the criteria for the layout, design, installation, and operation of flight deck facilities for transport aircraft.

3.5.1.2 Operational Requirements

Operational requirements are provided for flight deck layout, facilities, detailed design features, and windows. The flight deck layout should be designed to accommodate pilots ranging in height from 5 ft 2 in to 6 ft 3 in. The layout design should also provide access to all controls that are defined in ARP4102, "Flight Deck Panels, Controls and Displays." All primary controls should be located relative to the Design Eye Position (DEP). The facilities requirements include guidance on items that should be included in the flight deck such as seats, document stowage, writing equipment, and rest facilities for long flights. Some facility items include specific dimensions while others are more general in nature. The detailed design section specifies guidelines for preventing crew distraction, sealing of spaces, horizontal surfaces, flooring, leg clearance, footrest, injury protection, and pedestal and overhead panels. Criteria for flight deck windows include visibility, heating, and shielding of sunlight.

3.5.2 ARP4101/4 - Flight Deck Environment

This ARP specifies the transport aircraft environmental conditions needed to enable the crew to perform their duties and functions in comfort, with minimum fatigue, and without distractions. The operational requirements include specifications for ventilation, noise, vibration, and solar radiation.

3.5.3 ARP4102 - Flight Deck Panels, Controls, and Displays

3.5.3.1 Scope and Operational Requirements

The scope of this document is to recommend criteria for the design, installation, and operation of flight deck panels, controls, and displays. It is to be used for transport category aircraft. The operational requirements for this ARP are general in nature. For example, controls and displays should be simple, rational, and user-friendly to ensure effective and error-free operation. The requirements also mention the cases where controls and displays can or should be integrated.

3.5.3.2 Panels

This ARP provides details on the location and function as well as the display arrangement for the following panels:

- Pilot's Primary Instrument Panel,
- Center Instrument Panel,
- Glareshield Panel,
- Pedestal,
- Pilot's Overhead Panel,
- Third Crew Member's Panel, and
- Circuit Breaker Panel (information provided in ARP4101/5).

As an example, the Pilot's Primary Instrument Panel should be located directly in front of the pilot and as close to the windshield lower cutoff as possible. The latter criteria is required in order to minimize the pilot's vertical scan between the head-down displays and the outside environment. In addition, the panel should be oriented so that parallax is minimized and reflections and glare are prevented. Functionally, this panel should display vertical and horizontal situation, command information, and navigation data.

The display arrangement for the above panels specifies the location of the panels' respective components. For example, in specifying the display arrangement of the Pilot's Primary Instrument Panel, this ARP calls for the following:

- Pitch and roll attitude, flight path situation, and command information shall be displayed in the central upper area of the panel.
- In situations where the Primary Attitude Instrument (PAI) is located above the Primary Navigation Instrument (PNI), the PAI should be located no more than one inch from the vertical plane passing through the DEP and parallel to the longitudinal axis of the aircraft. When the PAI is located beside the PNI, the vertical center line of the PAI should not be more than 2.5 inches from the vertical plane passing through the DEP and parallel to the longitudinal axis of the aircraft.
- Airspeed and related parameters shall be displayed to the left of the center line. The location of a separate airspeed indicator is given relative to the horizontal center line of the attitude display. If the indicator is part of the Electronic Attitude Director Indicator (EADI)/PFD, the airspeed value should be aligned with the horizontal center line of this display.
- Altitude and related parameters (including glideslope and vertical speed) are to be displayed to the right side of the center line. The location of a separate airspeed indicator is given relative to the horizontal center line of the attitude display. If the indicator is part of the EADI/PFD, the altitude value should be aligned with the horizontal center line of this display.
- Basic navigation information shall be displayed in the lower central area. The present heading should be aligned with the vertical center line of the attitude/primary flight display.
- Stand-by instruments shall be located such that both pilots are able to monitor the instruments with minimal head movement.

3.5.3.3 Controls

This section provides criteria for flight deck controls including location of controls, operation of controls, and specific recommendations. Control operation is described for push buttons; control levers; slew, rotary, and toggle switches; keyboards; soft keys; touch panels; and voice recognition. Specific recommendations are given for automatic flight/flight guidance, wing flap, landing gear, speed brake, and ground steering controls.

3.5.3.4 Displays

This section of the ARP gives both general and fault alert guidelines for displays. In general, the displays are to be designed as a complete information system. Flight simulator studies should be performed on instruments and displays to ensure high efficiency and the elimination of design and human errors. Display details, control locations, quality, and multipurpose designs are also discussed. The fault alert criteria include alerts for individual displays, distinct indications between loss of signal and equipment failure, and the use of annunciation for systems containing Built-In Test Equipment (BITE).

3.5.3.5 Color

This section provides the color set to be used on panels, controls, and displays. These colors are red, tan/brown, amber, yellow, green, cyan, blue, magenta, and white. Coding for electronic displays is defined. It is noted that sufficient contrast must be maintained when using red, brown, or amber colors superimposed or placed close together.

3.5.4 ARP4102/4 - Flight Deck Alerting System

3.5.4.1 Scope

This document provides design criteria for the Flight Deck Alerting System (FAS). There are four levels of alerts defined for the FAS, level 0 through level 3. These levels are defined as:

- Level 3 - Warning (an emergency situation, e.g. serious system failures),
- Level 2 - Caution (an abnormal situation, e.g. failure with no immediate impact on safety),
- Level 1 - Advisory (recognition situation, e.g. failure leading to loss of redundancy), and
- Level 0 - Information.

3.5.4.2 Operational Requirements

In general, the FAS should possess a master aural attention-getting sound for alert levels 1, 2, and 3. The FAS should also contain one or more alphanumeric displays so that a corresponding message can be shown on the display during an alert. The urgency level of the alert should vary as a function of the flight phase and current aircraft conditions.

As part of the functional requirements, four types of alerts and their respective applications are described. The four alerts are aural, discrete aural, voice, and tactile. The aural alerts, also known as "attenson," are unique attention-getting sounds. The same sound cannot be used for different functions on the flight deck. The attenson is to be applied to level 2 and 3 alerts and

optionally to level 1. The sound is to be transmitted through cockpit speakers and crew headsets. The use of discrete aural alerts is not recommended for the FAS. The attenson, along with a display alert, is considered to provide a warning superior to discrete aural alerts. The voice alert is a warning method that can be used to supplement the aural alert and the display for level 3 time-critical alerts. A tactile warning (i.e. a stick shaker) is considered acceptable when it is supplemented by aural and visual alerts for Level 3.

3.5.4.3 Panels, Controls, and Displays

The panel that houses the FAS should be visible and accessible to both pilots when the flight deck seats are located such that the pilot's eyes are at the DEP. The control panel, if it exists, should include all the controls needed for the operation of the FAS.

Displays should include the FAS visual display and alerting lights. The FAS display should be alphanumeric. Its function is to supply an alphanumeric readout that will direct attention to an indicator or control device at another location. The initial alphanumeric readout should be cancelled automatically if the fault is corrected. The alerting lights of the FAS are to be an independent light system for each system or function monitored. These lights should consist of two bulbs that can be tested and replaced easily.

3.5.5 ARP4102/6 - Communications and Navigation Equipment

3.5.5.1 Scope

Recommendations are made for the control and display of flight deck communications and navigation equipment. This includes:

- Communications

Cabin/Service Interphones, Public Address (PA), Select Call (SELCAL), Call Select (CALSEL), Satellite Communications (SATCOM), and Ultra High Frequency (UHF), Very High Frequency (VHF), and High Frequency (HF) Radios;

- Navigation

Very High Frequency Omnidirectional Range (VOR), Tactical Air Navigation (TACAN), Automatic Direction Finder (ADF), Distance Measuring Equipment (DME), Instrument Landing System (ILS), Markers (MKR), Omega, Very Low Frequency (VLF) equipment, Inertial Navigation Systems (INS), Inertial Reference Systems (IRS), Satellite Navigation (SATNAV), and Low Range Radio Altimeter (LRRRA);

- Weather Radar; and

- Data Link

Company communications, ATC Transponders (Mode-S), and others.

3.5.5.2 Operational Requirements and Panels

The operational requirements are made up of guidelines for audio characteristics, communication equipment, and navigation equipment. The audio selector panels should be accessible to each crew member. Each pilot's panel should be visible to both pilots.

3.5.5.3 Controls

Guidelines are specified for audio, communication, and navigation equipment control. For example, controls for VHF and HF communications equipment are discussed. On the VHF radio, if a squelch control is needed it should be located next to the frequency selector. If the equipment has an automatic squelch control, a control to disable automatic squelching should be considered. Frequencies on the HF radio should be selectable in 1 kilohertz (kHz) steps.

3.5.5.4 Displays

Display guidelines are furnished for the audio, communication, and navigation equipment. For example, the UHF/VHF/HF communications equipment displays should indicate to each pilot all communication frequency and mode information. This can be accomplished on one display visible to both pilots.

3.5.6 ARP4102/7 - Electronic Displays

3.5.6.1 Scope

This ARP supplies recommendations for flight deck electronic displays on transport category aircraft. These electronic displays include electronic flight instruments, alert displays, aircraft system displays, and control/display units for flight management and radio management systems.

3.5.6.2 Operational Requirements

The electronic display must be legible while operating in all lighting conditions found in the flight deck and while operating in a monochrome or degraded mode. Displays on a pilot's panel that are required to be monitored by a third crew member should be visible and legible from his/her seated position. Data viewed on the display should always enter and leave the display in a smooth manner. When power fluctuations or power transfers occur, the display should operate without serious interruption. In addition, display content or values chosen by the pilot should not change.

3.5.6.3 Displays

General guidelines and specific details are supplied for the following types of displays:

- PFD/EADI,
- Electronic HSI/ND,
- Flight Management Display,
- Alerting Display, and
- Systems Display.

Generally, it is important to ensure that electronic displays have the proper lag time between the selection of data and the resulting display of data. Primary flight data should not experience more than a 1/4 second lag. For nonessential data, lag time should be four seconds or less.

The specific information to be presented on each display also is provided.

3.5.7 ARP4102/7 Appendix A - Electronic Display Symbology for EADI/PFD

3.5.7.1 Scope and Contents

This Appendix is an extension of ARP4102/7. It recommends the symbols to be used for the EADI/PFD. The geometry and location of these symbols are also provided. All symbol geometries are given in a table format. For example, figure 3.5-1 shows the recommended geometry for the Horizon Line. The table also includes some symbol alternatives and a remarks column that specifies symbol details. It should be noted that the specific dimensions of the symbols are left to the designer.

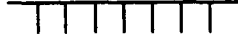

EADI/PFD			
NAME	RECOMMENDED SYMBOL	ACCEPTABLE ALTERNATIVES	REMARKS
1. HORIZON LINE			<ul style="list-style-type: none">• LINE SHOULD GO ACROSS THE ENTIRE ATTITUDE DISPLAY• TICS MARKS ARE RECOMMENDED WHEN A FLIGHT PATH VECTOR IS USED• TICS MARKS SHOULD BE EVERY 10°. THEY SHOULD BE OF EQUAL LENGTH

FIGURE 3.5-1. RECOMMENDED GEOMETRY FOR THE HORIZON LINE

3.5.8 ARP4102/8 - Flight Deck, Head-Up Displays

3.5.8.1 Scope

This ARP recommends criteria for the design and installation of HUD systems. The information that is included in this document applies to HUD systems that display flight data focused at infinity in the forward Field of View (FOV). This document does not deal with systems for peripheral vision or displays worn by the pilot (e.g. goggles and helmet sights).

3.5.8.2 Operational Requirements

HUD system operational requirements consist of general requirements, system requirements, and installation criteria. In general, the HUD system should provide a display that allows the pilot to determine aircraft attitude and flight path relative to and associated with external visual cues. The system requirements define the HUD's FOV, optical quality of the combiner, and integrity of the HUD. Installation criteria include guidelines to ensure proper HUD operation as well as guidelines related to safety.

3.5.8.3 Controls

The HUD system controls include ON/OFF (unless coupled with stowing action), MODE (unless automatic), and contrast or brightness.

The location of the controls should be on the primary display unit or on a dedicated panel situated close to the pilot. Additional controls associated with display parameters should be integrated with head-down instruments whenever possible.

3.5.8.4 Display Criteria

HUD systems can be used to repeat, augment, or replace Head-Down Displays (HDDs) for any or all phases of flight. The format used on the display should allow the pilot to transition from head-up to head-down quickly and easily. The operation of the system should be intuitive and require minimal training. In addition to providing basic information such as attitude, heading, flight path angle, airspeed, and altitude, the HUD display should provide:

- Visual Approach information,
- See-to-Land Instrument Approach/Go-Around information,
- Non-Visual Takeoff and Landing information, and
- Warnings (i.e. HUD system failure and input data failure).

HUD system displays also have associated symbology criteria such as symbol quality, character size, symbol accuracy, stability, and brightness.

3.5.8.5 Colors

HUD system displays should implement color only when there is an improvement over monochrome displays. If color is used, color selections should be consistent with those used for the corresponding symbol on the HDD.

3.5.9 ARP4103 - Flight Deck Lighting for Commercial Transport Aircraft

3.5.9.1 Scope and Requirements

ARP4103 recommends criteria for the lighting systems and the interface required for flight deck areas, controls, and displays. Operational requirements include instrument lighting; panels (lightplates); circuit breakers; warnings, cautions, and advisory system lighting; and general and utility flight deck lighting.

3.5.9.2 Lighting Controls and Locations

Lighting controls are to include brightness controls in addition to the requirements found in ARP4102, paragraph 5.3. Controls should be located conveniently for the appropriate crew member. The light switches that are to be controlled by both pilots should be placed so that both pilots can reach them while seated with seat belts fastened. Dome or ceiling light controls should be located on the light or near the doorway into the area to be lighted. The knobs for white lighting intensity controls should be transilluminated with a white engraved arrow on top. The only exception to this are instrument bezel knobs. Standby lighting controls should also be furnished. They are to be activated during loss of aircraft power using an emergency battery supply. The minimum intensity of these lights should enable pilots to read instrumentation. Guidelines are also furnished for storm lighting controls, emergency lighting, and circuit configuration for standby and emergency lighting.

3.5.10 ARP4105 - Abbreviations and Acronyms for Use on the Flight Deck

This document was developed to institute preferred abbreviations for terms used on panels, controls, displays, instruments, placards, and markings. These abbreviations and acronyms apply only to equipment used by crew members in the flight deck of transport aircraft.

Guidelines are given that specify punctuation marks, letter case, terms excluded, acronyms for common equipment components (e.g. P for Panel), metric system abbreviations, and length of abbreviations. These guidelines are followed by three tables. Table 1 defines Velocity Speed Abbreviations. Table 2 lists flight deck terms alphabetically with their corresponding preferred and alternative abbreviations or acronyms. Table 3 lists abbreviations and acronyms alphabetically with the corresponding meanings.

3.6 Summary

As part of the Cooperative Engineering Program, the SAE serves industry, government, and the public by developing guidelines and standards for design, manufacture, testing, quality control, and procurement. The SAE publishes the ASs, AIRs, ARPs, and other documents in order to advance the state of technical and engineering sciences. These documents, which are drafted by industry experts, are advisory in nature. They provide a source for related PVI information and references to other important reports, standards, and regulations. The ARPs are updated, on the average, every five years. With the constant addition of new documents and the updates to old ones, the SAE provides a reliable source for PVI-related information. The SAE document summaries included in this report provide the reader an overview of those documents. If additional information is needed, the corresponding document should be acquired from the SAE.

4. PILOT-VEHICLE INTERFACE TECHNOLOGY

This section examines some of the design tools used in the development and testing of aircraft cockpits. It also considers the various technologies relating to displays and controls in the modern transport cockpit. Particular focus is given to the digital facets of the input and output devices.

4.1 Cockpit Design Tools

Design of the cockpit necessarily involves the melding of numerous technologies relating to PVI. The diversity of these technologies, magnitude of the tasks, safety demands, cost, and other factors require the use of design tools to aid the design engineers in this challenging task. Design tools allow initial system development, testing, and modification to take place before a final product is produced. Changes made early in the design process have a significantly smaller impact on product cost than changes made later in the design process. Tools such as rapid prototyping and Computer Aided Design (CAD) assist the engineers in the design and development process.

The rapid configuration of a test environment is beneficial to evaluating new concepts, technologies, and cockpit arrangements. Displays, keyboards, and voice applications, as well as other issues such as lighting can be examined early in the design cycle. Also, the myriad human factors issues can be examined and problems can be identified and corrected before the product is manufactured.

4.1.1 Rapid Prototyping

Rapid prototyping allows a system model to be developed quickly and inexpensively. The prototyping can be done two different ways. One way is to develop a crude but working model of an entire system. The other is by developing a realistic model of the user interface, leaving out most of the internals of the system (Arkusinski and Hoenbach 1988).

Arkusinski and Hoenbach (1988) studied rapid prototyping in the development of CDUs. Mock-ups of CDUs for a navigation system were built to allow a test crew to "fly" the unit in simulation before production began. This approach allowed changes to be incorporated into the system at an early stage and avoided major overhauls late in the project. Through using a rapid prototype device, the study identified a number of problems that caused a display to be unacceptable:

- Related information displayed on different pages,
- Inappropriate formats (leading zeroes or blanks, upper or lower case),
- Trivial error or warning messages that should not be displayed; or error messages that should be displayed and are not,

- Unnatural flow between display pages,
- Poor page layout or cryptic information, and
- Unnatural sequence of keystrokes; repetitive, or too numerous keystrokes.

Desirable features of a rapid prototyping system include:

Modeling System Characteristics

- Ability to support user interface mechanisms;
- Ability to define all aspects of the interface;
- Ability to display characters as accurately as possible, including size, font, blinking, reverse video, color;
- Ability to model simple line graphics;
- Ability to output sound, such as for warnings;
- Ability to model events in real time;
- Ability to specify all aspects of the interface without having to write code; and
- Ability to modify the prototype easily.

Modeling State Transitions

- Fixed transitions, for example, after the last field on a page is entered, the next page automatically displays;
- Keypress activated transitions;
- Field-content dependent transitions; and
- Externally activated transitions.

Entry and Display of Data for Variable Fields

- Cycling text between a fixed number of options;
- Highlighted list with all possibilities displayed on the screen; a key toggles between choices;

- User-entered values, subject to range or value check;
- Alert messages that display when exceptional conditions occur; and
- Computer fields where the value from one field is computed from or based on the value in another field.

Other Requirements

- A portable system that can be transported to a customer site or can be accessed via modem,
- Ability to display the simulation on a large screen so that it may be viewed by many people during a meeting, and
- Ability to run on the customer's computer or on a microcomputer dedicated to that purpose.

4.1.2 The Computer Mock-Up

The Computer Mock-Up (CMU) is a flexible, inexpensive design tool that can be used in the phase between initial theoretical specifications and flight tests. Schumacher and Starke (1987) describe a CMU implemented as a full-size model cockpit for a light transport helicopter. Simulation models are initiated by user inputs. The aim of the tool is to collect information about the ergonomical design, technical realization, and operational ability of the future helicopter cockpit. Some advantages of using the CMU include (Schumacher and Starke 1987):

- Testing without flight clearance,
- Testing independent of weather conditions, and
- Testing with a large number of personnel to obtain reliable results.

4.1.3 Reconfigurable Cockpit

The Reconfigurable Cockpit (RCP) is a PVI design tool for simulating the hardware and software capabilities of a proposed crew station. The objective of the RCP is to be capable of emulating control, display, and operational logic available in advanced aircraft, yet remain flexible enough to allow rapid changes to be implemented. Features include a voice recognition control system and touch control technology. Some advantages of this system are:

- A rapid prototype system to create aircraft cockpit simulations,
- Man-in-loop evaluation of the generated cockpit,

- Many man-in-loop design iterations prior to baseline freeze, and
- Exploration of untested ideas.

A caveat for using design tools is to avoid limiting cockpit design to those elements that are easily modeled by the chosen software development system (Davis and Pencikowski 1988).

4.1.4 The Army-NASA Aircrew/Aircraft Integration Program

The Army-NASA Aircrew/Aircraft Integration (A³I) program is a joint Army-National Aeronautics and Space Administration (NASA) program to develop a prototype workstation. This prototype workstation would allow helicopter cockpit designers to appraise human performance capabilities and limitations during the early design phase of system development. The goal of the program is to provide the designer with an understanding of the environment in which the system will operate as well as a set of analytical tools to perform detailed analysis of specific elements of the modeled machine-human interactions (Hartzell and Lakowske 1988).

4.1.5 Computerized Biomechanical Man-model

The Computerized Biomechanical Man-model (COMBIMAN) system is an interactive computer-graphics human factors evaluation tool. Its purpose is to assist in the design and analysis phase of workstation development. The system can represent the geometric and physical properties of an operator and can be used to evaluate existing and conceptual workstation designs (CSERIAC 1992).

4.1.6 Advanced Technology Crew Station Program

The Navy's Advanced Technology Crew Station (ATCS) program has been implemented to develop, demonstrate, and validate a crew-systems interface that will integrate aircrews and technologies within the aircraft system. The goals of the program are to produce (Mejazak, Sparta, and Warner 1991):

- A validated crew-systems engineering method for designing integrated crew-systems,
- Tools for evaluation and definition of crew-systems performance requirements,
- Modification of aircraft weapon system specifications, and
- Advanced crew station concepts for the Navy's next generation tactical aircraft.

4.2 Cockpit Display and Control Technology

Aircraft control and navigation began by the pilot looking out the cockpit and on the world below. Minimal instrumentation was used in the early cockpits. The instrumentation used was

primarily for monitoring the engine and fuel states, as well as to provide some basic navigational information such as speed and direction. The read-out was usually in the form of a dial with a pointer, and located in the cockpit for observation by the pilot.

Until recently, the number of switches and electromechanical displays in the cockpit was increasing. New control and display systems driven by newer technologies were continually added to the cockpit. Although the added systems contributed to the safe flight and landing of the aircraft, serious doubts arose as to the pilot's ability to deal with the numerous stand-alone systems, along with their separate displays and controls.

While new technology was a contributing factor to the problem, it was also viewed as the solution. New methods of control were introduced through the use of the multifunction keyboard, eliminating numerous discrete switches. Switching from one system to another was now performed by the push of a button. These keyboards were interfaced to the many aircraft systems through data bus interfaces.

In addition, the introduction of the CRT display into the modern cockpit provided a means for eliminating the swelling number of electromechanical indicators. By the use of the CRT and suitable interface electronics numerous related stand-alone indicators were replaced by a single CRT. The CRTs were multifunctional so that any CRT could, by the turning of a switch, be used for a different function.

This section examines various cockpit display and control technologies. A number of display technologies are examined, along with the construction and operation of these devices. Failure modes are identified and the relative advantages and disadvantages are addressed. Implementations of these technologies in the cockpit, such as the HUD, are also examined.

4.2.1 Display Technology

The pilot obtains information about the state of all the monitored aircraft systems through some type of indicator or display. This section analyzes various technologies that are used in the manufacture of displays. Various display technologies are examined, such as:

- Monochrome and color CRTs,
- LC display,
- Electroluminescent (EL) display,
- Vacuum Fluorescent Display (VFD), and
- Alternating current (ac) and direct current (dc) plasma displays.

In addition, failure modes are identified and display interfacing techniques are examined.

4.2.2 Cathode Ray Tubes

The CRT was used prior to World War II to display raw analog signals from airborne radar and airborne radio navigation equipment (Hunt 1983). For instance, the CRT could display the return radar pulse from a target aircraft.

During the 1950s the need was recognized that more information concerning the target should be presented to the pilot of a combat aircraft. This, coupled with the need for the pilot to maintain visual contact led to the development of the HUD. Parameters such as airspeed and attitude could now be displayed to the pilot along with target-related data.

CRTs began to be used widely in many applications outside the aerospace field. Many advances were made in CRT technology including the development of the color CRT. At the same time, electromechanical displays were being replaced by the newer electronic displays using a variety of display technologies. These two paths began to merge as CRTs were used increasingly to integrate the cockpit information into a common display. The use of the CRT in the commercial transport cockpit has become the "norm" for information display, replacing many discrete displays. The fact that present generation cockpits are being referred to as "glass cockpits" confirms this trend.

The CRT dominates the arena of high resolution video display devices. It is capable of eye-pleasing animated displays and also is well suited for alphanumeric and graphic displays. Advantages of the CRT over other technologies for high-speed, high-resolution displays are many. These attributes and other advantageous characteristics of the CRT are:

- The CRT response time (bandwidth) and resolution satisfy viewer requirements for high quality dynamic image presentation.
- Scanning techniques are simple to implement. Scanning is also quite versatile, lending itself to raster, stroke, and random scanning.
- The CRT itself has few parts and a correspondingly small number of electrical connections.
- The CRT is versatile in its application. The same CRT may be used for alphanumerics as well as graphic information.
- Luminous efficiencies associated with CRTs are high when compared to other technologies.
- The CRT is easily mass-produced.
- Color displays can be presented on the CRT.

- The CRT is reliable and has a long life.
- The CRT presents information more rapidly and the cost of a CRT display system is low when compared to other technologies.

Some disadvantages of the CRT are:

- The physical dimensions of the tube make it awkward for mounting in certain applications.
- There are a limited number of practical gray shades.
- The detail contrast is degraded at high luminance levels.
- The CRT requires constant refreshing to avoid the problem of display flicker (Tannas 1985).
- The CRT is susceptible to High Intensity Radiated Fields (HIRF) effects.

A basic schematic diagram of the monochrome CRT is shown in figure 4.2-1. There are four fundamental parts of this CRT. These are the bulb, the electron gun, the deflection mechanism, and the screen.

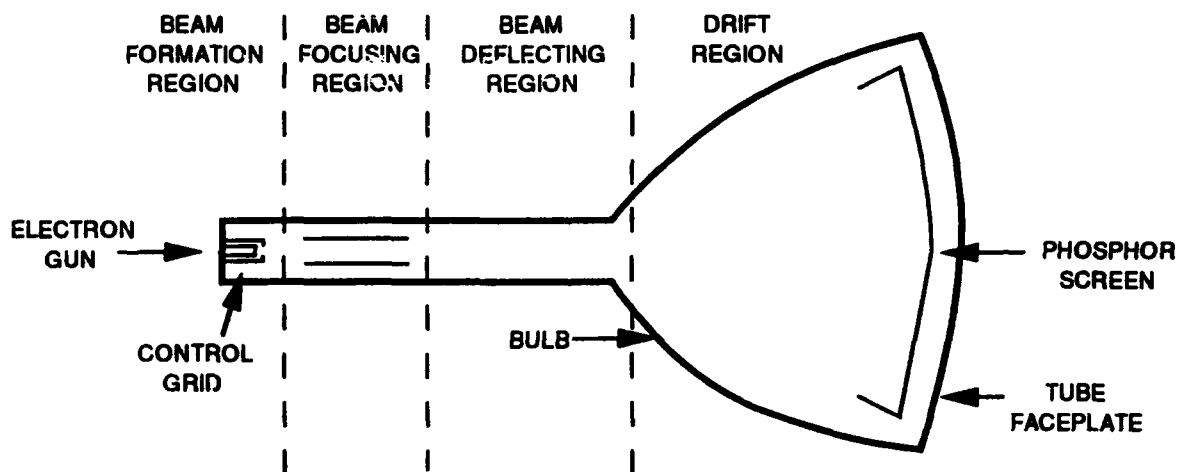


FIGURE 4.2-1. SCHEMATIC DIAGRAM OF MONOCHROME CRT

The bulb is made typically of glass and is evacuated for operation of the electron beam. It has a narrow neck which flares toward the front of the bulb where the display surface is located. The display surface consists of a clear faceplate upon which the phosphor for the viewing screen is

deposited. Modifications may be made to the face of the tube for safety reasons, such as implosion protection and emission reduction.

The electron gun supplies an intense beam of electrons which is focused and modulated along the path to the faceplate. Focusing can be accomplished either electrostatically or magnetically. The deflection mechanism is used to direct the electron beam, originating in the electron gun, to a particular location on the faceplate. Either electrostatic or magnetic deflection can be used. When electrons leave the deflection region, they enter the drift region. There are no magnetic or electric fields acting on the beam at this point, but the entire region is at the high voltage level of the screen. Electrons travel across this region and arrive focused on a spot on the phosphor screen.

The faceplate is the focal point for the beam of electrons from the electron gun. These electrons strike the phosphor particles coated on the faceplate causing light to be emitted. A thin film of aluminum is deposited over the phosphor and is used to establish the proper screen voltage.

The electron beam, which is generated by the electron gun when the proper voltages exist in the CRT, is accelerated, focused, and directed to various positions on the screen. As movement of the beam over the screen area occurs, the video information modulates the electron beam intensity in synchronization with the deflection mechanism. One of the grids of the electron gun is typically used for control of the beam intensity.

Due to the nature of CRT technology, continual refresh of the CRT screen is required. Typically this occurs 50 or more times per second and is driven by the requirement to present dynamic information and to eliminate the sensation of flicker to the viewer. This refresh rate depends on the characteristics of the phosphor used and the type of information being displayed.

4.2.3 Color Cathode Ray Tube

By modification of the basic elements of the CRT, color operation becomes possible. Several methods for color production exist. These are the mask, beam index, and penetration phosphor methods.

There are three main differences in the construction of a color CRT. These are the addition of two more electron guns, the addition of a mask between the guns and the screen, and the use of a specially coated screen.

4.2.4 Shadow-Mask Cathode Ray Tube

One particular mask technique is the shadow-mask. The basic principle of the mask technique can be seen by an examination of figure 4.2-2. This uses a metal mask placed between the three guns and the screen. The screen phosphor consists of sets of three dots arranged in a delta configuration. The electron beam of each gun passes through a particular hole in the mask at any given instant. Each beam then strikes the screen on its associated phosphor dot. Due to the

construction, the beam from one gun can only fall on one colored dot in the set of three. Hence, by feeding each gun with its independent signal, the three primary color guns can be modulated accordingly. Deflection of the three electron beams over the screen is handled by the same deflection yoke since the velocities, and hence the amount of deflection, of the three beams is the same.

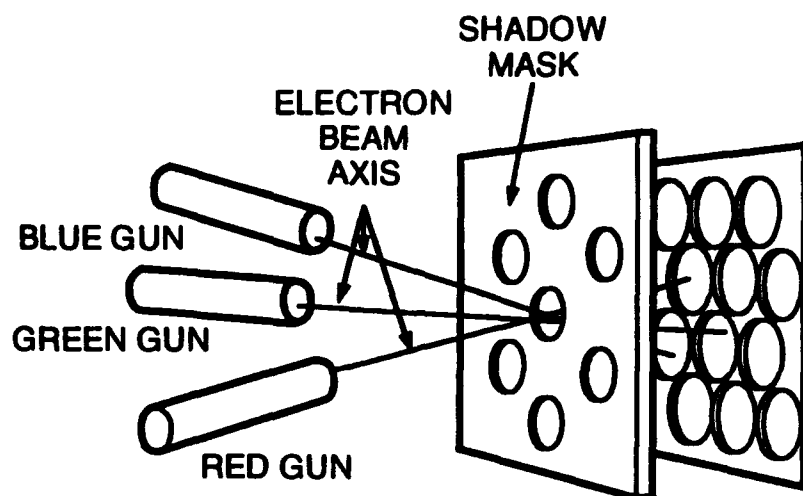


FIGURE 4.2-2. PRINCIPLE OF SHADOW-MASK CRT (Michel 1983)

A variation on the shadow-mask is the in-line gun Trinitron™ seen in figure 4.2-3. Here, vertical stripes of phosphor are coated on the screen in a continuous repeating pattern of the three primary colors. In addition, the electron guns are in a line instead of in the delta configuration. This particular technique has the advantage of improved vertical resolution and ease of convergence of the three electron beams. The size of the tube that this technique can be used in, however, is limited since the mask is not self-supporting (Tannas 1985).

Use of the shadow-mask in a CRT causes a loss of typically 70 to 85 percent of the average electron beam current. In the cockpit environment where high levels of ambient light may exist, higher currents are necessary to produce more luminance. This situation causes higher temperatures to be generated in the shadow-mask, which produce thermal expansion and may lead to a mis-alignment between the shadow-mask and the phosphor coated screen.

Another problem is apparent with respect to the display luminance characteristics. Red and blue phosphors do not have the luminous efficiency of green phosphors. This leads to more complicated design considerations.

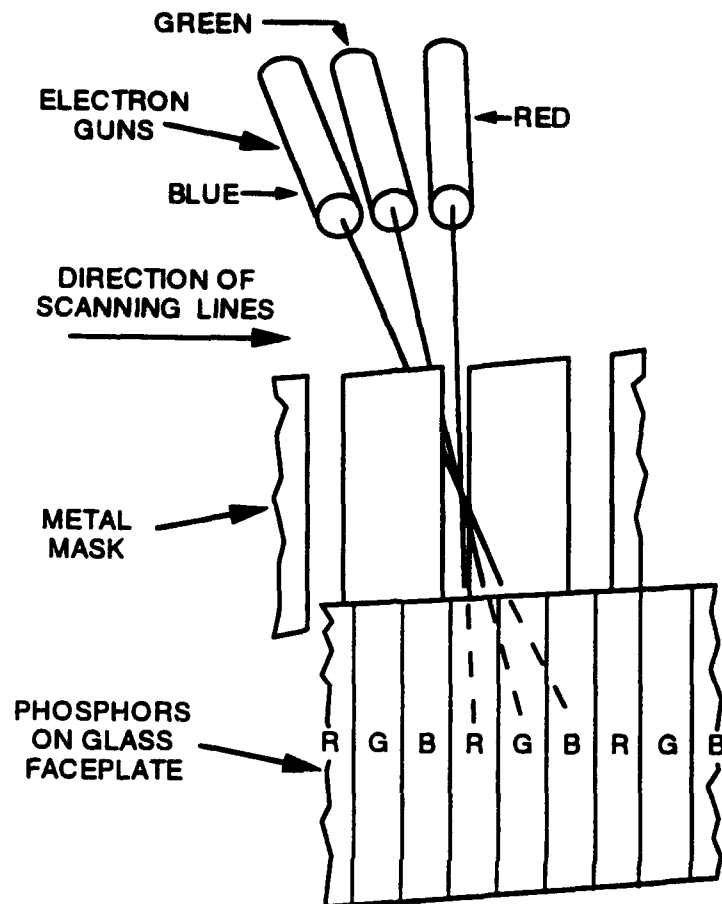


FIGURE 4.2-3. OPERATING PRINCIPLE OF TRINITRON COLOR CRT
(Tannas 1985)

An additional problem to be addressed in shadow-mask applications in the cockpit is that of vibration. Since the shadow-mask is very thin and full of holes, care must be taken in the CRT design to ensure that vibrations do not translate into movement of the shadow-mask. The effect of any mask movement would be misalignment in relation to the phosphor screen. The misalignment would then result in color impurity on the CRT screen.

4.2.5 Beam Index Cathode Ray Tube

This CRT avoids the problems associated with the use of the shadow-mask. It uses vertical stripes of phosphor on the screen with no mask between the gun and the screen. Indexing stripes are used on every fourth position between each set of three color stripes. A single electron beam, capable of being focused on the width of one phosphor element, is used. The indexing stripes are part of a control loop. When the beam falls on the indexing position, emission from this element is detected and used as a synchronizing signal for the deflection circuit. The beam current modulator is synchronized to the scan deflection timing through use of this control loop.

Emission from the indexing stripes is non-visible and typically Ultra-Violet (UV). Figure 4.2-4 illustrates the construction of the beam index CRT.

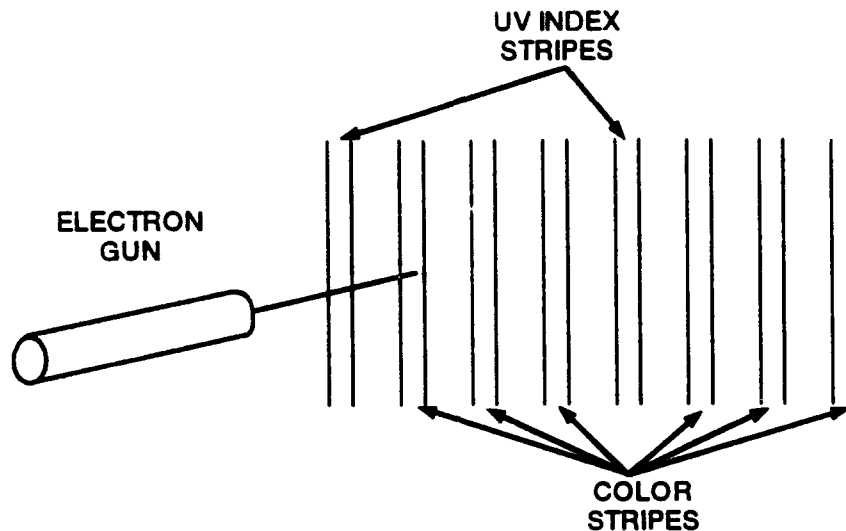


FIGURE 4.2-4. CONSTRUCTION OF BEAM INDEX CRT (Tannas 1985)

By design, the beam index CRT is lower in manufacturing cost, lighter in weight, lower in power dissipation, and higher in resolution than the shadow-mask CRT. However, it is difficult to maintain a sharp, constant-sized spot under varying beam intensities. There is no appreciable difference in the luminance since the beam remains on each phosphor stripe for less than 30 percent of the index-to-index time, where in the shadow-mask CRT the beam energizes the phosphor for the entire period.

4.2.6 Penetration Phosphor Cathode Ray Tube

The operation of this CRT is based on the principle that electrons traveling at higher speeds have a greater depth of penetration into solids than electrons traveling at lower speeds. Hence, for slower electrons the energy is absorbed near the surface and for higher speed electrons the energy is absorbed at a greater depth. This CRT is also simpler in construction than the shadow-mask and relies on the characteristics of the phosphor screen and electron velocity differences for color generation.

Figure 4.2-5 shows the basic construction of the penetration phosphor CRT. One layer of phosphor is deposited uniformly on the glass of the screen. Over this layer a barrier layer is deposited. On top of the barrier layer the second layer of phosphor is applied. A thin aluminum film is then deposited as the last layer. The aluminum film provides the acceleration potential for the electron gun.

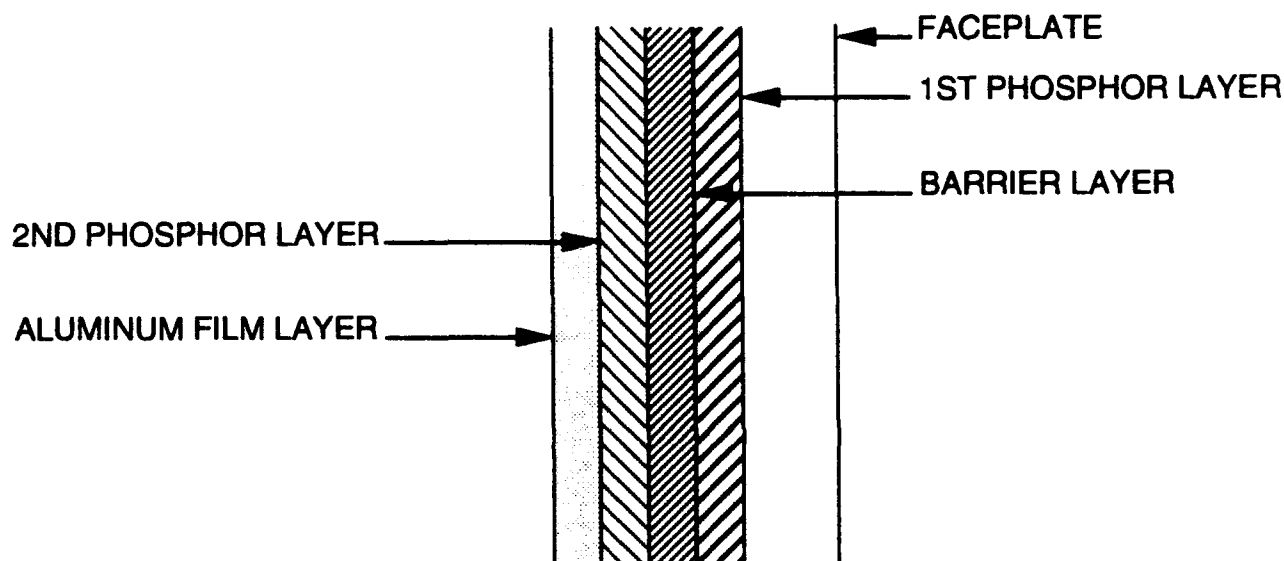


FIGURE 4.2-5. CONSTRUCTION OF PENETRATION PHOSPHOR CRT

With a low potential applied to the aluminum film layer, the electrons are absorbed in the aluminum and do not pass through to the phosphor layers. When the potential is increased, electrons pass through the aluminum and enter the second layer of phosphor where they are absorbed, causing luminescence of that layer. As the potential is increased further, electrons are partially absorbed by the second layer, while the remainder pass through this layer to the first layer. This causes the color generated to be a mixture of the characteristics of the two types of phosphors used. At the highest applied potential, the beam energy becomes sufficient to pass completely through the second layer and is entirely absorbed in the first layer which is deposited on the screen. The CRT now emits light based on the characteristics of the phosphor of this first layer.

The penetration phosphor CRT has the advantage of rugged mechanical construction and therefore is suitable for environments with a high amount of vibration. High resolution is another

advantage of this CRT. Resolution is limited by the size of the electron beam width (Michel 1983).

Several problems are characteristic of the penetration phosphor CRTs. The luminous efficiency of the phosphors used in the penetration phosphor CRT is greatly reduced when compared to their use in a monochrome CRT. This is because the layer two phosphor is operated at reduced efficiency and a significant portion of emitted light from this layer is absorbed by the layer one phosphor before it can reach the screen. Also, there is a low efficiency due to energy lost in penetrating the layer two phosphor when attempting to activate the layer one phosphor (Tannas 1985).

Further information on color CRTs can be found in DOT/FAA/PM-85-19, "The Development and Evaluation of Color Systems for Airborne Applications."

4.2.6.1 Cathode Ray Tube Beam Formation

The initial development of the electron beam takes place at the cathode of the electron gun. Electrons are emitted from this region when the cathode is heated to a temperature of 800 to 1000°C. The cathode is coated with a compound which enhances the emission of electrons from the surface.

The beam forming region of the CRT generally consists of a heater, cathode, and two grids as seen in figure 4.2-6. The heater maintains the required operating temperature for the cathode. Grid 2 (g2), sometimes referred to as the first anode, is located between the screen and grid 1 (g1). G1, located between g2 and the cathode, modulates the electron beam with video information.

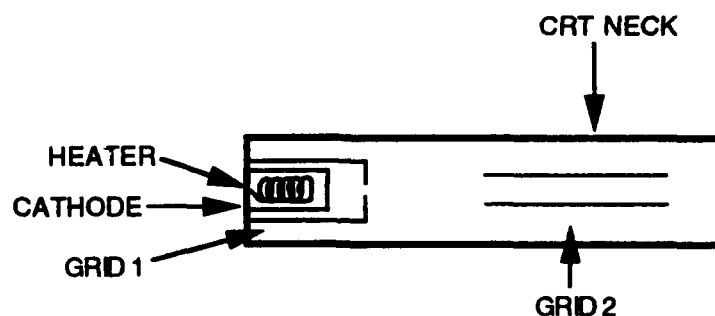


FIGURE 4.2-6. BEAM FORMING REGION OF CRT

4.2.6.2 Electron Beam Focusing

There are two methods for focusing the electron beam on the CRT screen. One is the electrostatic method and the other is magnetic focusing. These two methods of focusing are shown in figure 4.2-7.

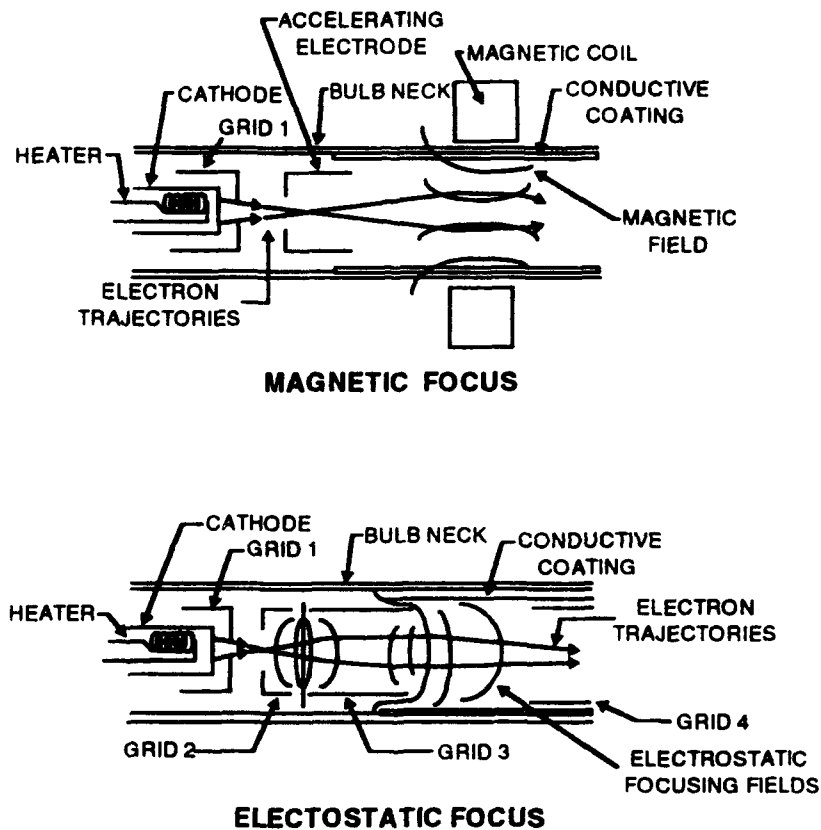


FIGURE 4.2-7. MAGNETIC AND ELECTROSTATIC FOCUSING METHODS
(Tannas 1985)

The magnetic method uses a coil which produces a magnetic field that is parallel to the longitudinal axis of the CRT neck. The electron beam enters the magnetic field resulting in the focusing action. Magnetic focusing yields the highest screen resolution, due to the uniformity of the magnetic field in the CRT neck.

Electrostatic focusing is implemented in two different ways. One is unipotential focusing and the other is bipotential focusing. The shape of the focusing electrodes and the magnitude of the applied voltages are used to focus the beam on the screen.

For bipotential focusing, 15 to 25 percent of the screen voltage is used for focusing. The focusing mechanism has two elements, one element between the g2 electrode and the focus electrode, g3, and the other located between focus electrode and g4 electrode which is maintained at the viewing screen voltage. Due to the high potential of the focusing electrode, the problems associated with grid currents may need to be addressed. With this focusing method, however, there is a 30 to 50 percent resolution improvement over the unipotential focusing lens.

With unipotential focusing the focus elements on both sides of the focus electrode are at the same voltage. A much lower focusing voltage is required. A negligible amount of current is drawn by the unipotential focusing grid (Michel 1983).

4.2.6.3 Electron Beam Deflection

Deflection of the electron beam over the screen area can be accomplished by using either magnetic or electrostatic fields acting on the beam. For magnetic deflection, a pair of coils is placed on opposite sides of the CRT neck. The magnetic field produced by one coil is oriented at a 90-degree angle from the other. Due to the orientation of the coils, deflection is controlled for vertical and horizontal movement of the beam. The amount of beam deflection produced is proportional to the amplitude of the current flowing in the coils.

Electrostatic deflection uses two metal plates placed at right angles to each other to provide horizontal and vertical deflection. The amount of deflection provided by this method is proportional to the voltages at the deflection plates and inversely proportional to the screen voltage.

Electrostatic deflection produces the highest speed deflection, with only moderate resolution. Slower deflection speeds are produced with magnetic deflection. The use of magnetic deflection and magnetic focusing provides the highest resolution CRTs.

4.2.6.4 Cathode Ray Tube Screen Refresh

Normally, CRT screens need to be refreshed continually by the electron beam. The refresh rate needs to be set to a value high enough so that the information presented does not appear to flicker. This refresh rate is typically 50 Hz or greater. The two common methods of refresh are raster scanning and stroke writing.

Raster scanning requires that the electron beam periodically sweep the CRT screen at the designed update rate. This sweeping of the screen by the beam is usually horizontal from top to bottom. This raster sweep pattern is shown in figure 4.2-8. Information is transferred to the screen by modulating the beam current with respect to the beam position. The beam current may take on any value from maximum to fully off.

Screen refresh may be line by line from top to bottom or every other line from top to bottom. The former method is the non-interlaced scan technique. A complete picture is presented each

time the screen is refreshed. The latter method is the interlaced technique. Only half of the screen image is presented for each complete scan by a refresh of every other line. Two complete screen scans will produce the full image on the screen.

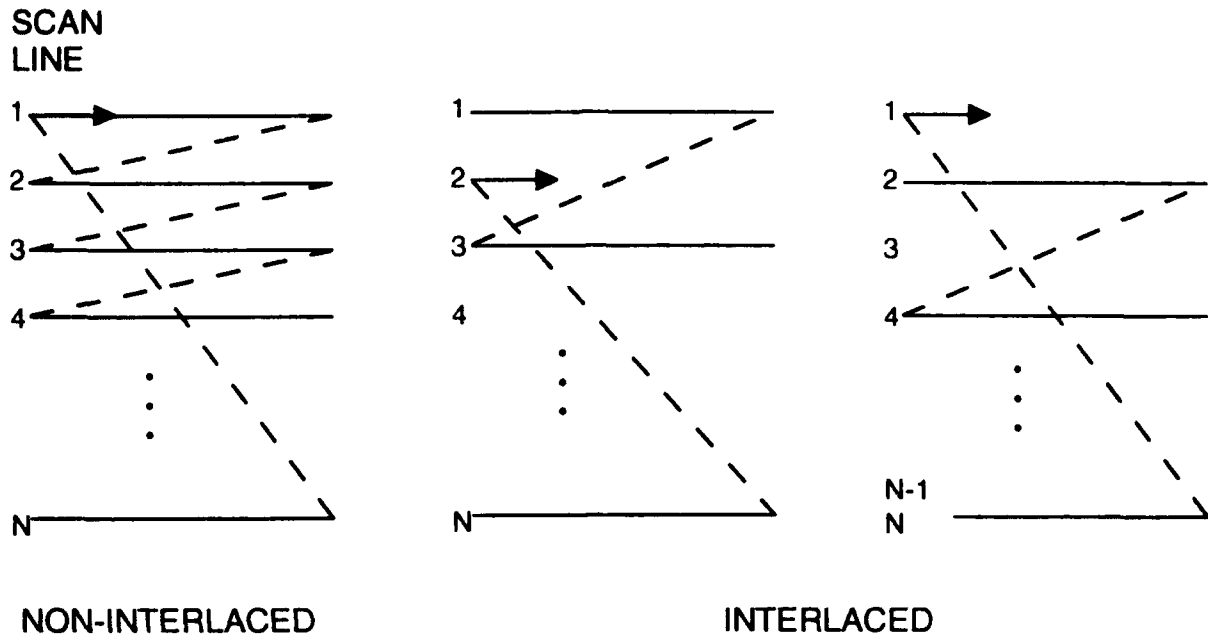


FIGURE 4.2-8. RASTER SWEEP PATTERN

Stroke writing is accomplished by directing the electron beam only to those areas where information is to be displayed. This requires that the beam be able to be directed randomly over the surface of the screen. A constant beam current is generally used along with a constant beam velocity to maintain constant screen brightness.

4.2.6.5 The Cathode Ray Tube Driver Circuit

CRTs have associated analog circuitry supporting the many functions required for operation. Typical circuits include the horizontal and vertical deflection, focus, high and low voltage, and the video and blanking circuits. Figure 4.2-9 shows a block diagram of a typical CRT driver circuit.

The horizontal and vertical deflection circuits amplify the input signal and drive the associated magnetic or electrostatic deflection devices in synchronization with the blanking circuit. The blanking circuit, which normally is connected at the cathode, turns off the electron beam during beam retrace times.

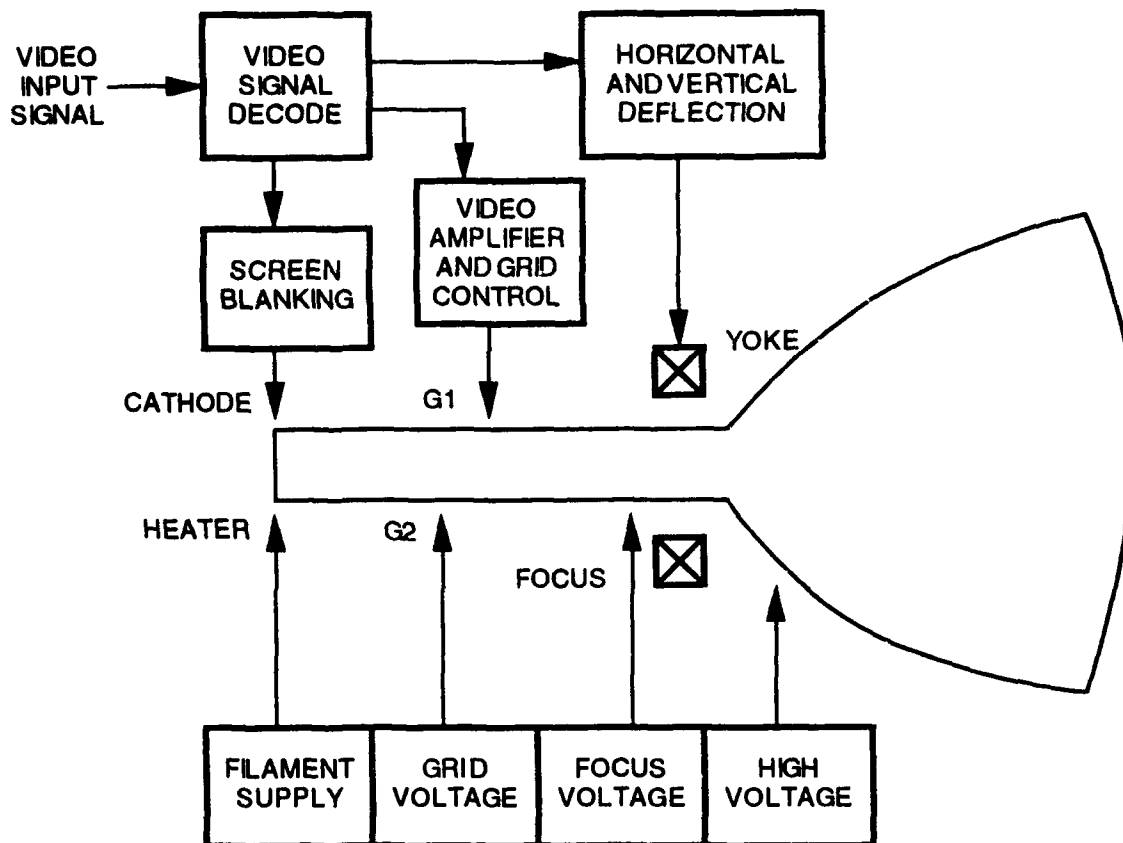


FIGURE 4.2-9. TYPICAL CRT DRIVER CIRCUIT

The filament and grid bias are both part of the low voltage CRT circuitry. Since the cathode and filament are in close proximity, the voltage difference between the two is a critical design constraint. A short between these two supplies can lead to total failure of the CRT. The g2 supply is also considered a low voltage supply, typically being several hundred to under one thousand volts. Sometimes the g2 and focus supplies are combined and are both operated at the same voltage.

The high voltage supply is used for the viewing screen and sometimes the focusing circuit. Since high voltages have an increasing tendency to arc under conditions of high moisture and dust and thus draw heavier currents, a limiting resistor in series with the high voltage supply is sometimes used for protection. Good voltage regulation in this supply is important for maintaining the designed CRT resolution.

G1 receives the video information and modulates the beam accordingly. The video information is occasionally introduced at the cathode, but this creates undesirable effects on the CRT resolution. Normal operation of g1 requires a negative biasing of the g1 grid with a voltage somewhere between cut-off and the maximum designed value.

4.2.7 The Flat Cathode Ray Tube

The flat CRT has been the design goal of intense research for many years. The design goals for the flat CRT are a flat format configuration for packaging considerations and improved performance when compared to the CRT. The main parts of the flat CRT are:

- Cathode,
- Beam positioning and modulation section,
- Brightness enhancement section,
- Phosphor, and
- Vacuum envelope.

4.2.7.1 The Flat Cathode Ray Tube Cathode

Many different methods for producing an efficient cathode have been tried by various research groups. The largest obstacle is the development of a cathode capable of supplying the required high beam currents. The standard electron gun of the beam deflection CRT is more than adequate for this purpose. Some flat panel construction techniques utilize a large-area cathode instead of the electron gun. This requires special consideration to maintain uniformity over the emission area.

4.2.7.2 Beam Positioning and Modulation

The beam positioning and modulation section is influenced by the design technique. Contrast, brightness, uniformity, and resolution are affected by these circuits. There are two main approaches used to accomplish modulation and beam positioning in flat CRTs. One uses the deflected beam method and the other uses a matrix method. Certain desirable features have been identified for each of these methods. These are listed in table 4.2-1 for matrix techniques and table 4.2-2 for beam deflection techniques.

Many different techniques for beam positioning and modulation have been tried by various manufacturers. Failures are often attributed to poor performance or high complexity. Even if the technical difficulties can be overcome, cost often becomes the limiting factor.

TABLE 4.2-1 DESIRABLE CHARACTERISTICS FOR MATRIX FLAT PANELS
(Tannas 1985)

Matrix Approaches
<ul style="list-style-type: none"> • Nonuniformities should not be introduced by whatever technique is used. • The beam spot size, switching, and modulation characteristics should be uniform over the display. • Live update rates should be possible. • The number of drivers required should be minimized. • The controlled parameters should interface with low cost ICs. • Cells should respond to applied modulation uniformly and have a wide dynamic range. • The technique should allow for different size and performance displays. • The technique should allow for mass production.

TABLE 4.2-2 DESIRABLE CHARACTERISTICS FOR DEFLECTED BEAM
(Tannas 1985)

Beam Deflection Approaches
<ul style="list-style-type: none"> • Deflection circuits should be low power. • The number of discrete power supplies and control circuits should be minimized. • Beam positioning should be very precise. • Any inherent distortion should be easily correctable. • Characteristics of the resolution, luminance, contrast, and modulation should be independent of screen location. • The beam should be controllable over a wide dynamic range and have a smooth response to the control input. • High speed deflection is required for live update rates. • Low voltage modulation and low driving capacitance are desirable for reduced power and high bandwidth displays. • The technique should allow for mass production.

4.2.7.3 Brightness Enhancement

Sunlight readability is a major requirement for a cockpit display and therefore brightness enhancement techniques are important for any flat panel design considerations. Various methods have been tested with this end in mind.

One of these methods is multiple-beam addressing. With the color CRT three beams are used, one for each primary color. With devices that are matrix addressed, this is an effective technique since it can be used in conjunction with the addressing of a complete row of the display.

Another method is to use an electron multiplier. This relies on the secondary emission principle, which basically states that when an accelerated electron strikes a surface, free electrons will be generated. The number of free electrons depends on the accelerated electron velocity, the material composition, and other factors.

The internal storage technique has been used successfully in the design of displays. One method involves the use of a storage capacitor with a Thin-Film Transistor (TFT) matrix addressed display cell. The capacitor stores the cell information until it is addressed again, yielding a decrease in the duty cycle and a corresponding increase in luminance.

4.2.7.4 Phosphor Screens

The flat CRT has the benefit of readily available, low cost, multiple color-generating phosphors. Color flat CRTs can be built using the three color phosphorus technique, beam penetration, and current-sensitive phosphors. In addition, with a matrix addressed flat CRT the registration problems associated with the shadow mask CRT are eliminated due to the inherent registration (Tannas 1985).

4.2.7.5 The Vacuum Envelope

One of the major problems to be reconciled with the flat panel CRT is the physical construction of the vacuum envelope. It is difficult to construct the envelope with a flat surface that is able to withstand large pressures. In addition there is the need to pass electrical connections through the envelope while maintaining a good vacuum seal. Depending on the type of CRT, there may be the need to pass hundreds of leads through the glass envelope, as in the case of a matrix addressed display.

Conventional CRT technology has improved faster than that of the flat panel. For this reason, much of the research in flat panel technology has produced little fruit with regard to modern display devices. The VFD is one of the successful products of flat panel research. This will be examined in section 4.2.11 of this report. It also appears that the Active-Matrix (AM) LC thin panel display will fill the display void of the flat CRT, since it answers many of the drawbacks of that device.

A taut shadow mask color CRT has been developed by Tektronix for use in military aircraft. This CRT uses a shadow mask which is under very high mechanical tension. A benefit of this CRT includes higher tolerance to vibration than commercial shadow mask CRTs. Additionally, due to the special construction, there is little purity loss due to thermal expansion of the shadow mask when compared to commercial shadow mask CRTs.

4.2.8 Light Emitting Diode Displays

The Light Emitting Diode (LED) is a semiconductor diode, based on the Gallium Arsenide (GaAs) compound, which emits light under the proper conditions. It is composed of two types of material, one an n-type and the other a p-type. When the p-n junction of the LED is forward biased with the correct potential, the electrons move from the n-side conduction band to the p-side Valence band of the LED. When the energy gap (E_g) is crossed, the electrons give up energy in the form of heat and light. GaAs diodes emit energy in the near Infrared (IR) region. In order to produce energy in the visible region, Gallium Phosphide (GaP) is combined with the GaAs. The GaAs radiation is absorbed by the GaP and visible light is emitted.

LEDs are classified as emitting light at certain discrete wavelengths. A typical spectral distribution of light emitted from a GaAsP LED is given in figure 4.2-10. Red light is emitted from the LED under forward biasing. Emission intensity reaches a peak at 650 nanometers and falls off rapidly above and below that wavelength.

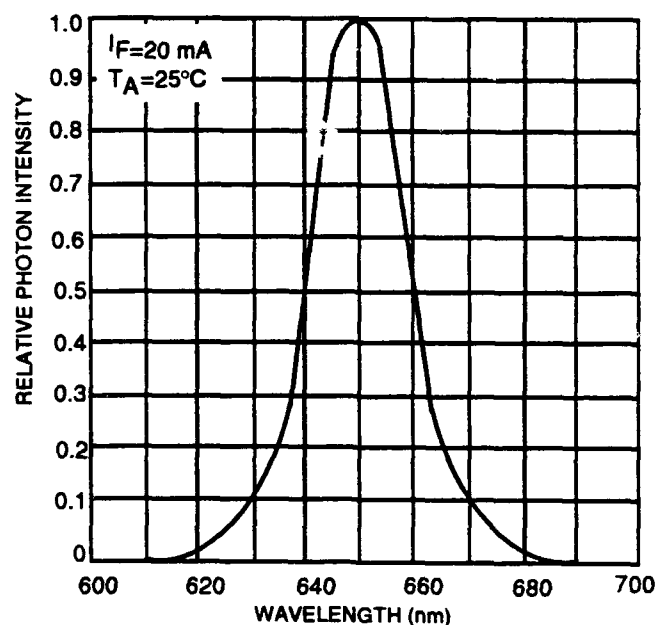


FIGURE 4 2-10. RELATIVE SPECTRAL CHARACTERISTICS OF A GaAsP LED
(TI Optoelectronics Data Book 1984)

The relationship between E_g and the wavelength of the peak emission of the LED is given by:

$$\text{Wavelength } (\lambda_{\text{peak}}) \cong 12380 / E_g \text{ Å}$$

Table 4.2-3 lists various compounds of Gallium, having differing E_g values, along with their respective emission frequencies and associated colors.

TABLE 4.2-3 LED MATERIALS AND WAVELENGTHS

Material	Wavelength	Color
GaAs:Zn	9000 Å	infrared
GaAsP ₄	6600 Å	red
GaAsP ₅	6100 Å	amber
GaAsP ₈₅ :N	5900 Å	yellow
GaP:N	5600 Å	green

The basic schematic representation of a circuit containing a single LED is shown in figure 4.2-11.

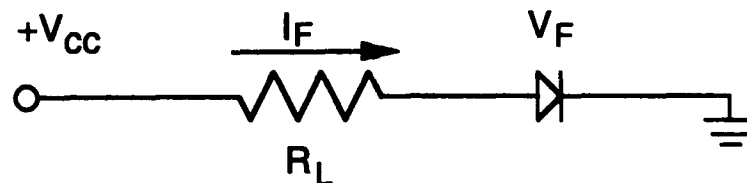


FIGURE 4.2-11. SCHEMATIC DIAGRAM OF LED

The LED is basically a current-controlled device. It has properties similar to diodes and needs current limiting to ensure the current does not exceed the operating limits of the LED. R_L provides that service by a series connection with the LED. Some LEDs are fabricated with R_L integral to the LED structure itself. The correct value of R_L is given by the following equation:

$$R_L = (V_{CC} - V_F) / I_F$$

The values of V_F and I_F are found on the respective data sheets for the particular LED device. Using typical values of 5 volts for V_{CC} , 1.6 volts for V_F and 20 mA for I_F yields a value of 170 ohms for R_L . Variations in R_L cause variations in the current flowing through the LED. Figure 4.2-12 shows how these variations in current can affect the luminous intensity of a typical GaAsP LED.

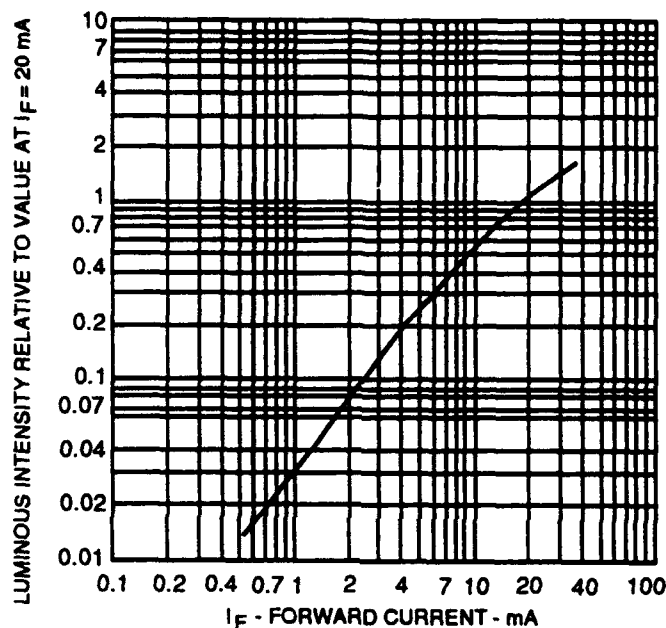


FIGURE 4.2-12. RELATIVE LUMINOUS INTENSITY VERSUS FORWARD CURRENT
(TI Optoelectronics Data Book 1984)

LEDs are manufactured as both discrete and monolithic devices. Discrete LEDs may be used in many ways in a cockpit, including status indicators and keyswitch backlighting for keyboards. Monolithic LED displays are used in numeric, alphanumeric, graphic, bar, and other geometric configurations.

Graphic arrays can be made by creating high density arrays of LEDs in a single monolithic circuit. A difficulty with this method is achieving electrical isolation of the individual diodes. A second manufacturing method is to bond the individual monolithic LED array Integrated Circuits (ICs) to a common substrate. Once this is done, the rows of anodes are electrically connected across the substrate and then routed to an external connector along with the discrete cathode connections. A third technique in the fabrication of graphic LED arrays is to create a hybrid assembly of discrete LEDs using automatic placement equipment.

A difficulty which needs to be addressed in the design and manufacture of LEDs is that of optical crosstalk. When monolithic displays are made on transparent substrates, optical coupling occurs when light generated by an active LED appears at an adjacent LED which is not active. This light appears at the adjacent LED position by traveling through the transparent substrate and then reflecting from the metal contact at the back of the LED. Figure 4.2-13 illustrates this optical crosstalk problem.

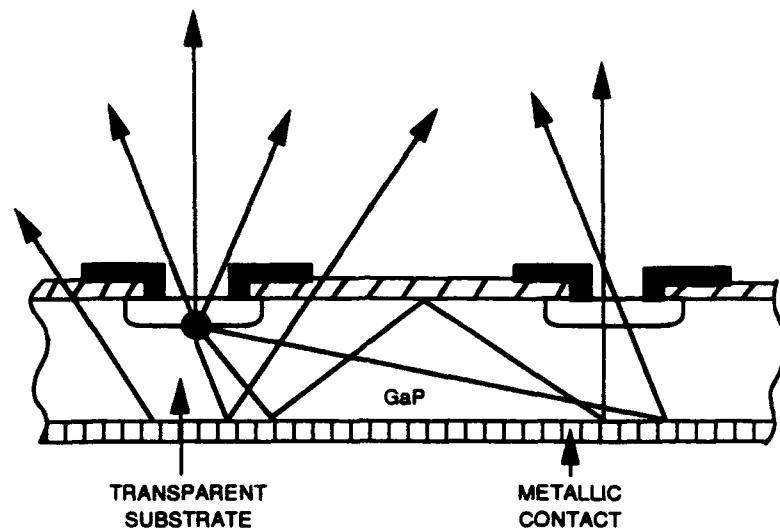


FIGURE 4.2-13. LED OPTICAL CROSSTALK (Tannas 1985)

4.2.8.1 Luminance Characteristics

The amount of light emitted by an LED is determined by the current density of the LED. Therefore, the current required to produce a given level of light is directly proportional to the junction size of the LED. In the manufacturing process, this parameter must be controlled to maintain luminance uniformity across a display. The voltage applied to the LED establishes the minimum power supply voltage required. The value of V_F , which is the voltage drop across an LED, may be as high as 3.5 volts. The efficiency of the circuit is determined by the LED and driver circuit operating characteristics (Prince 1983).

The LED luminance versus operating current becomes nonlinear due to two factors. These are the thermal characteristics of the junction, and a luminance saturation due to the junction current density. A temperature rise produced by current flow can be generated by numerous thermal design factors. Two such factors, the thermal conductivity of the LED substrate and the substrate bonding techniques play an important role in luminance linearity (Prince 1983).

4.2.8.2 Luminance Control

For cockpit applications, a method of controlling the LED luminance over a wide range is required. The LED linear luminance versus operating current characteristic benefits the LED for use in low ambient light conditions, such as night flying or when used with Night Vision Goggles (NVG). In these applications it may be necessary to implement a dimming control range of 2,500 to 30,000 for the current source to meet dimming requirements. For good control at the low output end of the luminance range this means that 27,500 current steps may be necessary. This would require the use of a control device with 15 bits of resolution for current control. Linear operation of the current control device is important to eliminate luminance uniformity problems (Prince 1983).

A common technique used to meet display dimming requirements is to control the time duration of the LED current flow. This pulse duration control allows flexibility in the average drive current supplied to the LED. This type of control is easily implemented with common digital logic circuitry.

4.2.8.3 LED Failure Modes

The Texas Instruments Optoelectronics Data Book contains data used by designers of LED circuits. It identifies parameters which can cause device failure, not just during use of the device, but also during shelf life, manufacturing, and testing. Typical parameters which the designers and manufacturers need to keep in mind when designing with LEDs are:

- Reverse Voltage,
- Continuous Forward Current,
- Peak Forward Current,
- Operating Free-Air Temperature Range,
- Storage Temperature Range, and
- Lead Temperature.

What is specified for a device is the absolute maximum rating at a given temperature, normally 25°C. The first four items in the list specify the operational parameters while the last two are concerned with the storage and manufacturing environment. The maximum lead temperature is specified to prevent device destruction in the soldering process. It is given as the maximum lead temperature at x distance from the device base for y seconds.

If the current density of an LED is exceeded, excessive junction temperatures will be produced. This can lead to permanently altered luminance/current density characteristics or complete device

destruction. Also, exceeding the reverse breakdown voltage by a sufficient amount will destroy the device. Reverse voltages of five volts or less will destroy most LEDs (Catalog of Optoelectronic Products, 1985). Proper design will reduce the probability of any of these failures.

4.2.8.4 Driving and Interfacing the LED

When LED graphic display modules are used, they are normally wired as common anode or common cathode circuits. Figure 4.2-14 shows a common anode connection for a small array of LED devices.

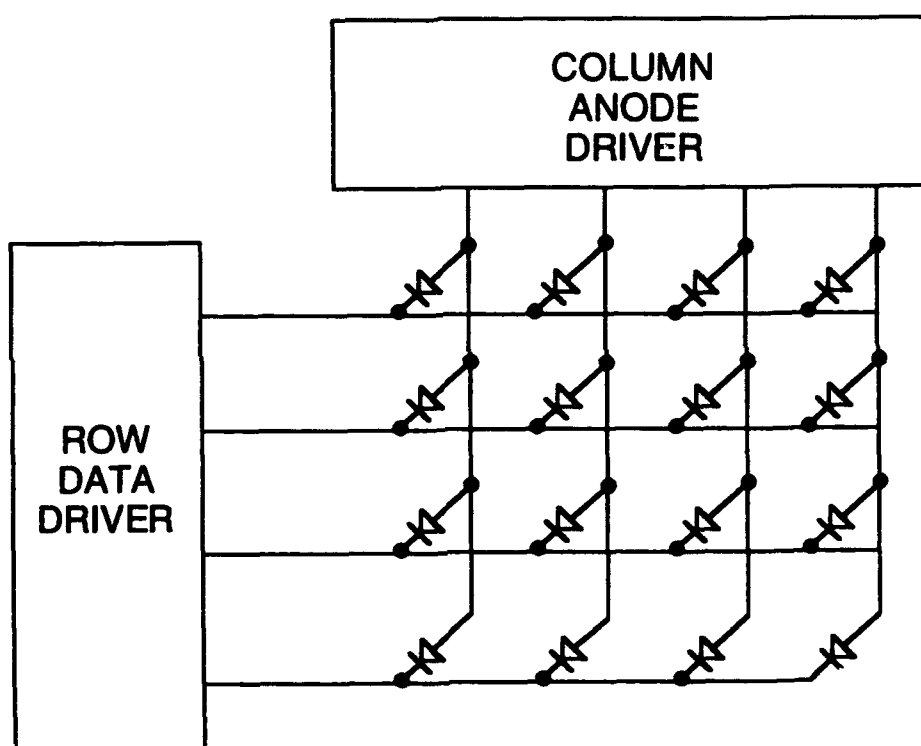


FIGURE 4.2-14. COMMON ANODE CONNECTION OF LEDs
(TI Optoelectronics Data Book, 1984)

Instead of using one driver for each LED, in this arrangement, arrays of LEDs are scanned. Data are placed on all rows by the row driver and refresh circuit. The data placed on the rows, however, are for one and only one column. The column driver for that row is then enabled for the time corresponding to the scan period. The data on the rows are latched and do not change for the entire scan period. After this, the data on the row drivers are updated for the next column

and the scanning continues. The drivers must be able to handle the peak currents of the LED matrix.

In order to maintain display luminance uniformity, the driver must supply a constant saturation voltage to the LED array whether only one, or all seven LEDs in the column are active. Keeping low values of resistance in the common driver circuit is important to maintain a constant luminance under varying current loads. One method to effect this is to physically mount the drivers on the sides of the display itself. When this is done, power loss is kept to a minimum and interface to the display is simplified.

Brightness control may be implemented in figure 4.2-14 by controlling the amount of time that each column driver is active. This is easily implemented using conventional design methods and available logic. If graphic arrays with gray scale capabilities are desired, however, then the method of driving and controlling brightness becomes more complex.

Display flicker can be a problem for designs incorporating LEDs. Other display technologies that require periodic refresh also must deal with this problem. There is a frequency, known as the fusion frequency, above which the eye no longer perceives this refresh effect. Display designers need to account for this as well as other factors that may have an effect, such as vibration of the aircraft.

Table 4.2-4 summarizes the disadvantages of LED display technology while table 4.2-5 summarizes the advantages of LED display technology.

TABLE 4.2-4 DISADVANTAGES OF LED DISPLAYS
(Tannas 1985)

- | |
|---|
| <ul style="list-style-type: none">• High power consumption (compared with passive displays),• High peak currents for long digit strings,• Restricted color range (difficult to produce commercially viable blue),• Cost of complex assembly (one die attach and/or wire bond per display element). |
|---|

Due to their many advantages, such as low cost and reliability, LED displays are commonly used in cockpits. They are used as status indicators, alphanumeric displays, and in HUDs as secondary display drivers in case the main CRT fails. They may also be used in Helmet Mounted Displays (HMDs) and in keyboards (Prince 1983).

TABLE 4.2-5 ADVANTAGES OF LED DISPLAYS
(Tannas 1985)

Appearance/Format
<ul style="list-style-type: none"> • Active, light emitting, • Color range (red, orange, yellow, green), • Size range (2-25 mm.), • Excellent viewing angle compared to liquid crystals, • Flexible format, • Multiple colors with a single device, • Sunlight viewability with appropriate filter.
Performance
<ul style="list-style-type: none"> • High Efficiency, • Large dynamic current range, • High response speed.
Interface Electronics
<ul style="list-style-type: none"> • Diode characteristics simplify matrix addressing, • TTL-compatible for current and voltage, • Wide range of available interface circuits, • Practically no duty cycle limitation, • Direct drive from CMOS for some applications.
Reliability/Environmental Range
<ul style="list-style-type: none"> • Rugged, not fragile, • Generally gradual, noncatastrophic failure, • Wide temperature range, • Long operating life, • Hermetic (optional).

4.2.9 Liquid Crystal Displays

LC displays hold great promise for use in avionic cockpits. This technology yields lighter displays that use less power and are easily read in conditions of high ambient light. Significant advances have been made in the technology of liquid crystals in recent years. Much of the research has focused on the AM LC display which has active elements (transistors) associated with each pixel.

4.2.9.1 Physical Properties of Liquid Crystal

Long thin organic molecules, having a general shape resembling a cigar, are normally used for the liquid crystal substance. In a liquid, the positions and orientations of molecules are essentially random. For crystalline solids, they are well defined. The orientation of the liquid crystal molecules is relatively well defined, but the positional ordering varies. The liquid crystal exists in various phases such as nematic, smectic, and cholesteric. Figure 4.2-15 shows a diagram of these different phases.

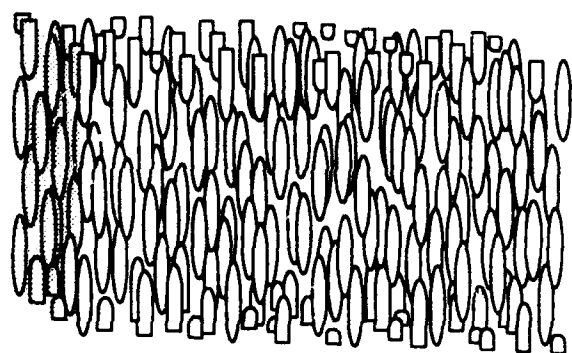
In the smectic liquid crystal material the molecules exist in layers, but the orientation order within the layer varies. Also, the layers can move relative to each other. Positional ordering is lost in the nematic liquid crystal but the orientation remains constant. Most commercial devices rely on the nematic liquid crystal phase. In the cholesteric phase various planes similar to the nematic phase exist, but the orientation of the molecules of each plane is slightly different.

The orientation of the liquid crystal molecules is represented by the director, which is simply an arrow in the same plane and pointed in the same direction as the molecules. For the cholesteric phase, the orientation changes resemble a helix structure.

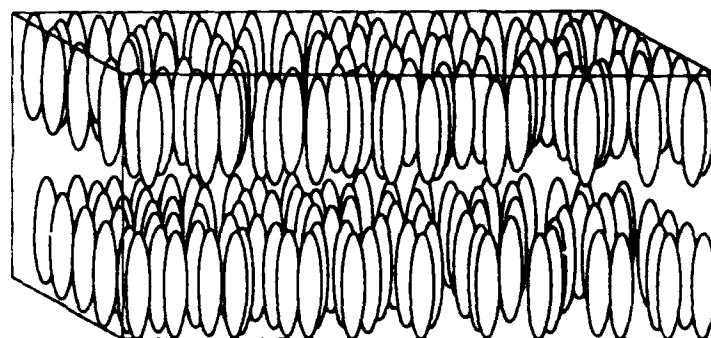
There are some interesting properties of liquid crystals that manufacturers utilize in the fabrication process. Liquid crystals exhibit anisotropic characteristics. For instance, an electric field or a magnetic field can be used to control the orientation of the director. This particular electric field property is used in the manufacturing process to create displays.

Another property of liquid crystals is the tendency to interact with solid surfaces. In order for the liquid crystals to be useful in display applications, a uniform orientation at the surface is required. By special treatment of the interacting surface, the director may be aligned either parallel or perpendicular to the surface. This property maintains the alignment of the liquid crystal in the absence of an applied electric field.

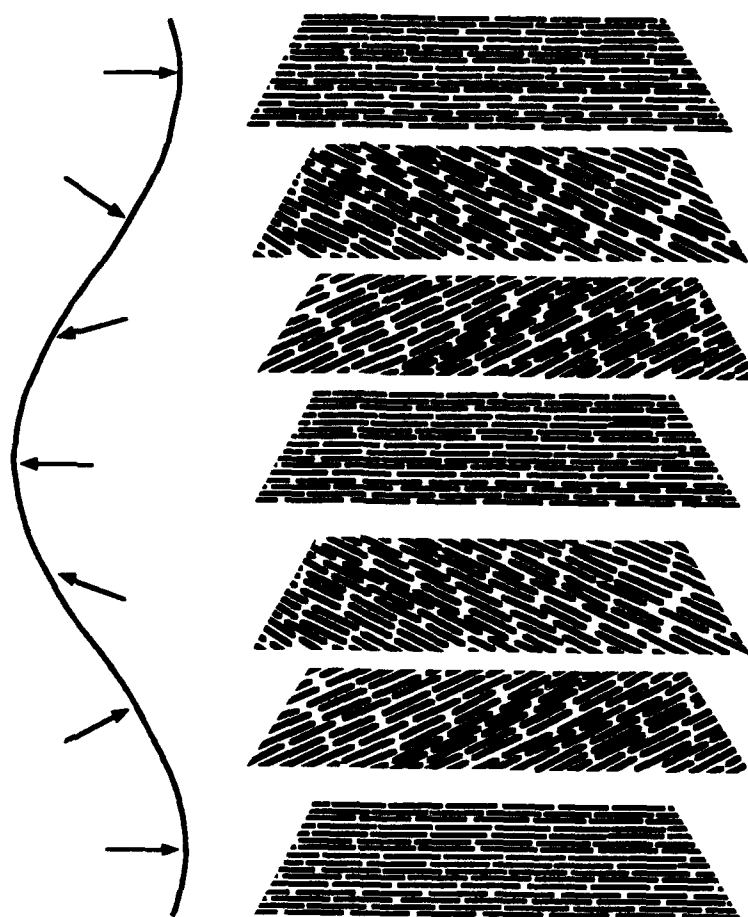
The liquid crystal is enclosed by flat glass substrates with uniform spacing. The liquid crystal material should be non-toxic and stable in any possible operating environment. On the inside of the glass the electrode patterns are formed. If the display is transmissive, a thin layer of transparent conductive material is used. For a reflective display, a metallic deposit may be used as the rear electrode.



NEMATIC PHASE



SMECTIC PHASE



CHOLESTERIC PHASE

FIGURE 4.2-15. PHASES OF LIQUID CRYSTAL (Tannas 1985)

Temperature has a great effect on the liquid crystal material. At low temperatures, the material may change into another liquid crystal phase, or even into a solid. Response times of the material decrease dramatically with lower temperatures. Figure 4.2-16 shows the relationship of temperature to the turn-on and turn-off times of a Twisted Nematic (TN) display cell. This effect necessitates the use of a heater in low temperature operating environments. At high temperatures the material becomes an isotropic liquid and the display properties are lost.

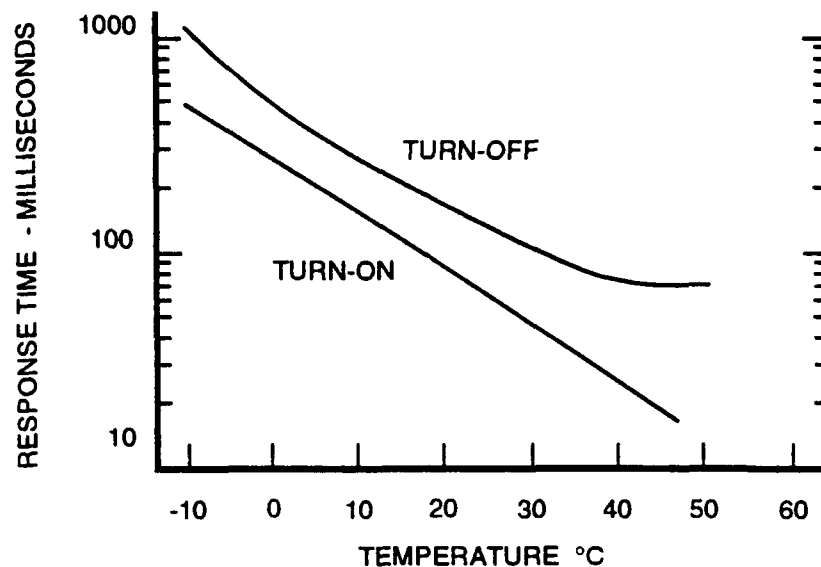


FIGURE 4.2-16. RESPONSE TIMES FOR A TN LC CELL (Hughes 1983)

The better liquid crystal materials exhibit an impedance of more than 10^7 ohms per square cm in parallel with a capacitance of 1000 to 3000 picofarads per square cm. The resistivity is generally greater than 10^{10} ohm-cm. Due to these properties, the power dissipation is limited to several microwatts per square cm (Hughes, 1983). Power consumption of liquid crystal displays is much less than other popular display technologies. Power supply requirements are lower, display volume is smaller (compared to the CRT), and less heat is generated by the display, reducing the cooling requirements for the cockpit.

4.2.9.2 Twisted Nematic Liquid Crystal Display

The TN LC display is one in which the liquid crystal molecules at one surface are turned 90 degrees from the other surface. One method of accomplishing this is to coat the two surfaces with a polymer which is then rubbed in the proper direction. Due to the surface interaction

property of the liquid crystal, it undergoes an alignment change of up to 90 degrees between the two surfaces, for the twisted effect.

Polarizers are used on the glass surfaces. They are parallel to the liquid crystal orientation at each respective surface. In the unenergized state, the polarized light enters the cell and rotates along the twisted path to emerge orthogonally polarized at the opposite surface, there passing through the other polarizer.

When the cell is energized, the liquid crystals are aligned in the same direction by the electric field. Light passes through the first polarizer and the liquid crystal, but does not undergo the rotation which was previously caused by the liquid crystal twisting effect. Hence, the light does not change polarization and is not permitted to pass through the second polarizer. In this manner a dark image is formed on a light background. If the polarizers are placed parallel to each other then a light image on a dark background is formed.

The Supertwisted Nematic (STN) LC display is variation of the TN. The degree of twisting produced in the liquid crystal is from 180 to 270 degrees, typically. A STN liquid crystal cell works on the birefringence principle, where the light is split into two components, each traveling at different speeds. Polarizers at each surface are used, but they are not aligned parallel with the liquid crystal at the surface. The cell thickness is also designed so that in conjunction with the polarizers and birefringence, a specific color is produced on the display.

4.2.9.3 Dichroic Dye Liquid Crystal Display

In this type of display, a black dye is added to the liquid crystal. The dye molecules align themselves parallel to the liquid crystal host molecules. When the display is not energized, all incident and transmitted light is absorbed by the dye. When the display is energized the dye molecules are aligned with the liquid crystal molecules perpendicular to the display surface, allowing the maximum amount of light to pass through the display.

The dichroic LC display can operate in a transmissive or reflective mode. In the transmissive mode, a light is fixed on the far surface of the display from the viewer. This makes the display readable in low ambient light. In the reflective mode, the display is read using ambient light. An energized cell appears darker and the contrast is enhanced in high ambient light.

4.2.9.4 Addressing the Liquid Crystal Display Matrix

In a liquid crystal display where there are a large number of cells which need to be addressed, it is common to use multiplexing techniques to reduce the number of connections. For a graphic array of 5 by 7 cells, there are 35 connections to be made if a discrete driving arrangement is used. Using multiplexing, this may be reduced to $5 + 7$ or only 12 connections. Figure 4.2-17 shows a common method for addressing a matrix liquid crystal array.

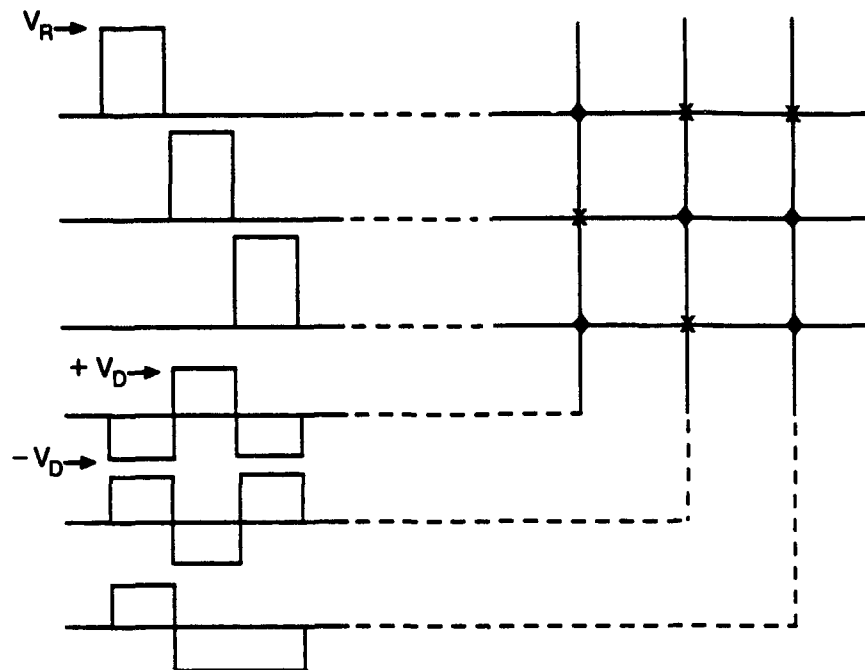


FIGURE 4.2-17. MATRIX ADDRESSING OF LC ARRAY
(Hughes 1983)

Each row is in turn scanned by the row select pulse, V_R . While this is going on, each column is pulsed with either a select or deselect waveform of amplitude $\pm V_D$. The potential difference between V_R and V_D causes the activation of the selected cell. Since ac drive is preferred for liquid crystal cells, the polarity of the drive signals may be reversed during the next scan time, or each pulse can be replaced by an alternating waveform (Hughes 1983).

Matrix addressing puts the select pulses on cells which are not activated as well. This necessitates careful choice of V_R and V_D so that display contrast can be kept high. Other problems associated with directly multiplexed displays are reduced viewing angle and other characteristic variations with temperature changes. The response time of the liquid crystal cell also causes severe limitations with respect to live update rates.

The advantages and disadvantages of LC displays are summarized below:

Advantages of LC displays:

- Do not emit light and do not suffer washout from high ambient light as other displays do,

- Require much less power to operate and hence use smaller, lighter, less expensive power supplies,
- Operate on low voltage, and are compatible with digital drivers,
- Have a long life expectancy,
- Are cost competitive, and
- Can be directly viewed or projected.

Disadvantages of LC displays:

- The liquid crystal phase exists for only a limited temperature range. Heating of the display is required in cold environments.
- The display response is slow at lower temperatures.
- The most common method of LC display, the TN effect, requires polarizers which limit the display brightness.
- The TN LC displays require the use of matrix addressing with a limited number of lines. Active element addressing is required for complex displays (Hughes 1983).

4.2.9.5 Active-Matrix Liquid Crystal Display

The AM liquid crystal technology has evolved considerably in recent years. For the AM cell, an active device is placed at each pixel, which is defined by the crossing of a row and a column line. Typically, a TFT as well as a capacitor are used. Figure 4.2-18 shows a cross sectional view of the TFT LC cell.

The polarizers are used for TN operation of the display. A layer of glass encloses and seals the front and back of the display. Proper uniform spacing is maintained between the two glass layers by spacer rods. Light entering from the back of the display passes through the polarizer, glass, and the transparent TFT matrix circuit. Light which passes through an enabled LC cell then passes through the color filter, glass, and front polarizer of the display. The TFT output electrode is composed of Indium Tin Oxide (ITO) which acts as a transparent electrical conductor. In this design, the TFT and associated circuitry are deposited directly on a glass substrate in a vacuum chamber. This sometimes yields short circuits between the gate and data lines. In order to overcome this, some designs incorporate two layers of glass, one for the gate lines and the other for the data lines. Pixel defects may be reduced by duplicating both the TFTs and the driver lines. An opened driver line will have no effect since the proper signal will still appear on the redundant line. A TFT that tests defective at this stage of the manufacturing process may be removed or repaired (Luo 1990).

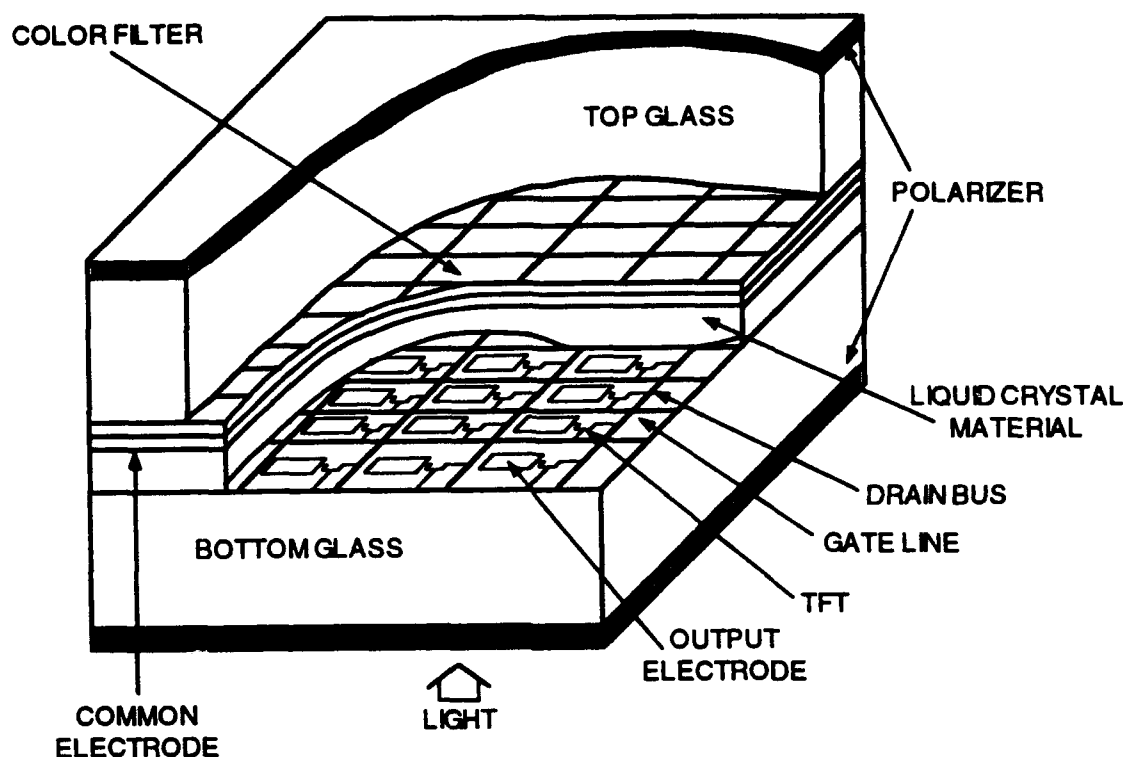


FIGURE 4.2-18. CROSS SECTIONAL VIEW OF TFT LC DISPLAY (Luo 1990)

The TFT is a Field Effect Transistor (FET). A matrix of TFTs is formed by connecting together the rows of FET drain connections and the columns of FET gate connections. Matrix addressing is then used to address the total number of rows in sequence. A positive pulse is applied to a particular row, enabling all the TFTs of that row. The TFT acts as a switch and charges its associated capacitor with the display data on the columns. When other rows are being addressed, a negative voltage is applied to the gate, turning off the TFT. The charge which is on the capacitor remains until the row is again addressed with new data.

It is important to maintain the state of the capacitor between successive refreshes. The current which flows through the TFT when it is in the OFF state should be small enough so that the appearance of the display is not affected. For panels that use bi-level voltages, the pixel gate voltage in the OFF state should not exceed the threshold level and turn the pixel on. Also, the pixel gate voltage in the ON state should not decay to a level where it may appear partially on or off. The charge on the LC capacitor may also leak through the LC material. In order to reduce the effect of this leakage, a capacitor may be added to the output electrode. This in turn will increase the circuit complexity and cost, and reduce the yield, as well (Luo 1990).

A color display requires proper alignment of the color filter with the pixels in the TFT array. Different types of color filters have been developed for this application, but the most widely used is the dyed gelatin color filter. This is used to form a layer between 1 to 2 μm in thickness. It is dyed three separate times for the red, green, and blue colors (Luo 1990). The color pixels are fabricated in patterns that correspond to their respective TFT electrodes.

An additional, but important part of the AM LC display is the backlighting device. An efficient, uniform light of highly variable output is needed for this display. An efficient lamp will produce more light with less heat. Uniform output is required so that the display does not appear brighter in one area than another. A variable output is required so that the display may be viewed in direct sunlight as well as during night flying. A florescent lamp with peak output at the red, green, and blue wavelengths is commonly used for this purpose. The overall display efficiency is enhanced when the spectrum of the backlighting source is matched with that of the color filter.

As with any liquid crystal device, operation at low temperatures requires special consideration. Response times of an LC cell progressively decrease with temperature and are in the range of 1 to 2 seconds at -40°C . Operation in cold environments requires the use of an integral heater for satisfactory response times.

The AM LC display technology is seen as the one that will replace the CRT in aircraft cockpits. Some military cockpits are already using this technology, with devices developed by Optical Imaging Systems. Both new designs and retrofits of existing aircraft are planned. The same trend is occurring in the commercial transport arena with Boeing planning to use AM LC for the primary displays of the Boeing 777. If the manufacturing cost for AM LC approaches the cost of the CRT, the AM LC display could completely eliminate the CRT in the cockpit.

A display device in development which marries the technologies of both the CRT and LC is the Liquid Crystal Shutter (LCS) from Tektronix. This device has a LC shutter placed over the face of a single electron gun CRT. Color is generated by switching a series of polarizing filters on and off during the normal screen refresh for each of the three primary colors. The color field rate is maintained at 180 Hz so that all three colors are updated at 60 Hz. The viewer's eye integrates each color frame and hence sees the full color images.

The LCS is designed for military aircraft and flight simulators. Since it uses a monochrome, high intensity CRT, the beam convergence problems of the multi-gun CRTs are non-existent. In addition, this display benefits from the LC characteristics of high contrast and sunlight readability.

4.2.10 Electroluminescent Displays

EL is light emitted by a phosphor in the presence of an electric field. Both ac and dc sources may be used to generate this effect. Thin-film phosphors, which are highly transparent, are well suited for creating complex displays on glass with a high contrast background. Being non-linear

in the luminance versus applied voltage characteristic makes Thin-Film Electroluminescence (TFEL) an ideal candidate for matrix addressing with digital electronics.

Construction of the TFEL display is done in layers. A transparent conductor layer is first deposited to allow for matrix driving. A dielectric is placed over this, followed by the phosphor material. A black thin-film layer is optionally deposited next. Another dielectric layer is then deposited, followed by the final conductor layer for matrix driving. Figure 4.2-19 shows the sandwich type construction of the TFEL display.

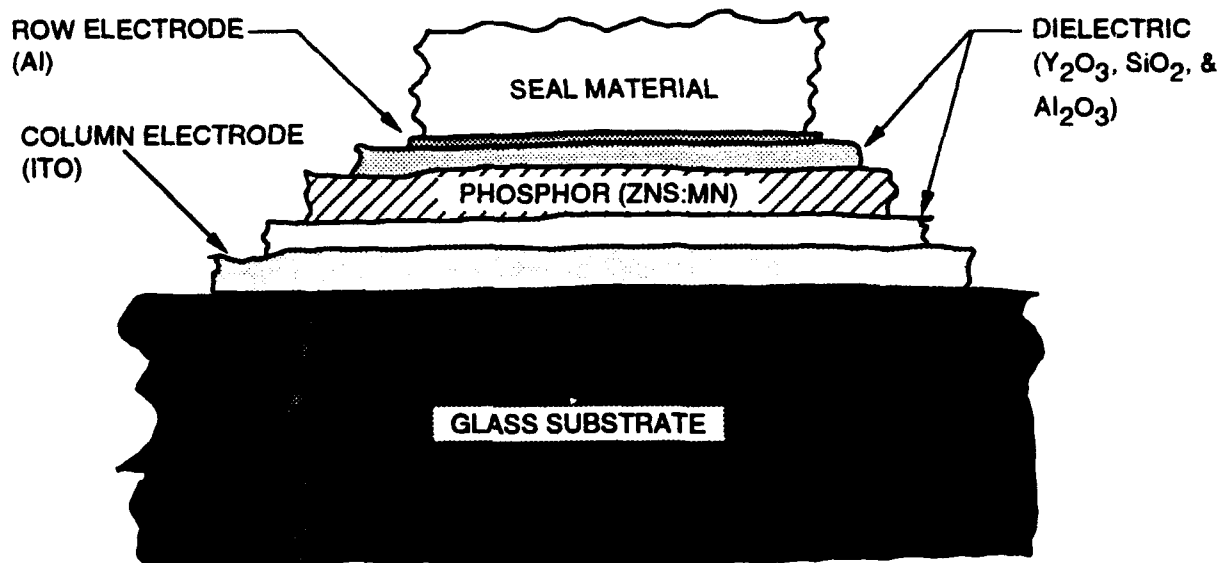


FIGURE 4.2-19. TFEL SANDWICH CONSTRUCTION (Tannas 1985)

When a large electric field is placed across the structure, the phosphor layer breaks down rapidly into avalanche conduction. A charge builds on the dielectric layers and the conduction of the phosphor layer diminishes. When the field is reversed, the same process occurs. Light is emitted by excited atoms in the phosphor material.

Additional space is required on the display glass for the hermetic seal and electrical connections around the outer edges of the display area. This requires about 1 cm of additional length and width. If driver ICs are added to the assembly, then additional depth may be required. The thickness of the display panels is generally less than 1.25 cm (Gurman 1983).

4.2.10.1 Reliability

Reliability depends on the quality of material used for the phosphor and that of the dielectric layers. Materials used need to be free from contaminants. The TFEL structure can be very sensitive to moisture, and requires care in the sealing process. Pin holes in dielectric can cause local burn-out damage due to high conduction currents there. This damage however is self-limiting, generating an open-circuit at that point and preventing further damage.

4.2.10.2 Failure Modes

The TFEL display acts as a capacitor due to its construction. In the active display area a high voltage rapidly charges the capacitor plates (the dielectric layers). If breakdown occurs, a high current flow will result, with the possibility of device failure due to the high amount of heat generated at this breakdown point. The larger the dielectric area is, the greater the amount of energy transferred into the breakdown area.

The overall efficiency of the TFEL display depends not only on the composition of the phosphor material, but also on the display driver circuitry. The row and column drivers are required to switch high voltages in short times, especially when using matrix addressing. This results in inefficiencies due to the largely capacitive loading that the TFEL cells present.

4.2.10.3 Addressing and Driving

The waveform of the driver is generally not critical, but a large electric field needs to be generated for light emission. A multi-element display may be driven several ways. One of these is to use matrix addressing. This method has a low duty factor since all rows need to be addressed before display refresh can resume. This method yields a lower luminance output due to the low duty factor of the matrix addressing technique.

If, however, a TFT is integrated at each pixel, several advantages are gained:

- Increased duty cycle of pixels, to 100 percent,
- Reduced line address voltages to CMOS compatible levels,
- Memory capability added to the display, and
- Separate power input from the signal input (Tannas 1985).

Figure 4.2-20 shows the electrical model for the matrix EL display.

Row and column intersections define a single pixel. Lines and columns are modeled as distributed column resistance (R_c) and row resistance (R_r) between each pixel.

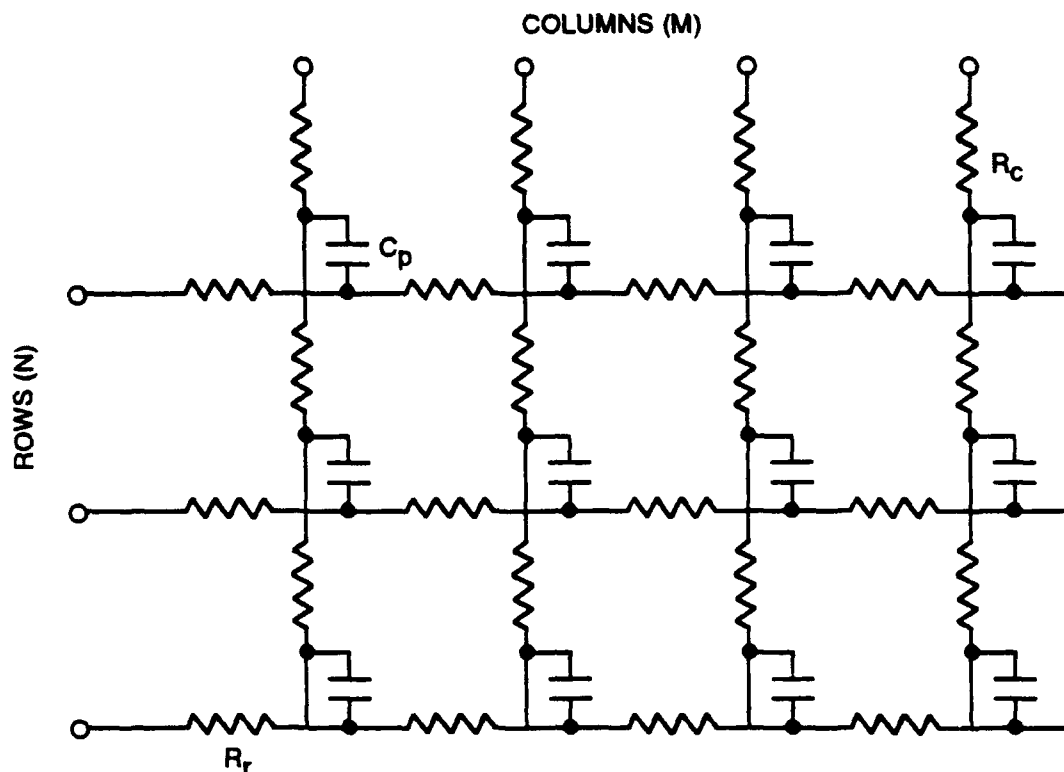


FIGURE 4.2-20. MATRIX EL DISPLAY ELECTRICAL MODEL (Gurman 1983)

Each pixel is modeled by a Pixel Capacitor (C_p) in parallel with a non-linear resistor. The non-linear resistor models the non-linear luminance property of the EL display and is generally ignored for analyses. Since each pixel is capacitively coupled to all other pixels, when the drive voltage is applied, all pixels are charged to some degree. Some of the pixels that are not selected may be charged to a level that causes them to emit light. This effect is known as crosstalk and can be eliminated by proper drive circuit design (Gurman 1983).

Most displays operate in the binary mode with pixel either completely on or completely off. Graphic and video displays can be produced by using a driver system capable of producing gray shades on the display. The TFEL display emits a short burst of light upon application of the high voltage waveform. Before the next pulse can occur, a pulse of the opposite polarity must be applied to the TFEL cell. Essentially, the device requires an ac waveform. It is possible to control the luminance by varying the frequency at which the display is operating (Gurman 1983).

Display flicker can occur at low refresh rates or under any other condition that may produce a stroboscopic effect, such as high frequency vibration. High resolution displays can be achieved with EL technology.

Color can be achieved with TFEL technology by the use of color activators in the phosphor material. Some of the colors and their characteristics are listed in table 4.2-6. The generation of blue is the most difficult due to the low luminance level and the low sensitivity of the eye to this wavelength.

TABLE 4.2-6 TFEL COLOR DISPLAY PERFORMANCE
(Tannas 1985)

Phosphor Coactivator	Color	Excitation Frequency, kHz	Luminance, fL
ZnS:Mn/TbF ₃	Red	0.06	4
ZnS:TbF ₃	Green	5	700
ZnS:TmF ₃	Blue	5	0.5
ZnSe:Mn	Yellowish-orange	1	30
ZnS:PrF ₃	White	2.5	60
ZnS:DyF ₃	Yellow-white	2.5	20
ZnS:DyF ₃	Yellow	5	140

Due to the transparency of the TFEL, it is possible to produce color displays without the loss of resolution characteristic of most other display technologies. Other display technologies, such as the shadow mask CRT sacrifice resolution when color areas are added to the display screen. With TFEL it is possible to place the different color cells in series without sacrificing the resolution.

Two other types of EL technology are used to produce displays. They are ac powder EL and dc powder EL. In ac powder EL, an alternating current is applied across the light emitting layer. This layer consists of Zinc Sulfide (ZnS) and Zinc Selenide (ZnSe) phosphor with copper sulfide as the key ingredient. The ac powder EL devices are low-luminance and are commonly used to light keyboards and panels. Higher luminance output is possible but the display life decreases rapidly.

The dc powder EL uses ZnS as a host material and Manganese (Mn) as an activator with a copper sulfide coating. A thin layer of phosphor formed next to the anode emits light through the transparent anode conductor. The dc powder EL is a limited resolution device and the overall efficiency in varying ambient light conditions is low. The life of the dc powder EL devices also decreases rapidly with use.

4.2.11 Vacuum Florescent Displays

The VFD is regarded as a type of flat CRT. This display technology relies on the same principle as the CRT, where light is emitted from phosphor coated anodes. Much lower energy levels are used in VFDs compared to CRTs. The display patterns are formed by discrete anode elements, rather than a focused electron beam. Figure 4.2-21 shows the typical construction of the VFD.

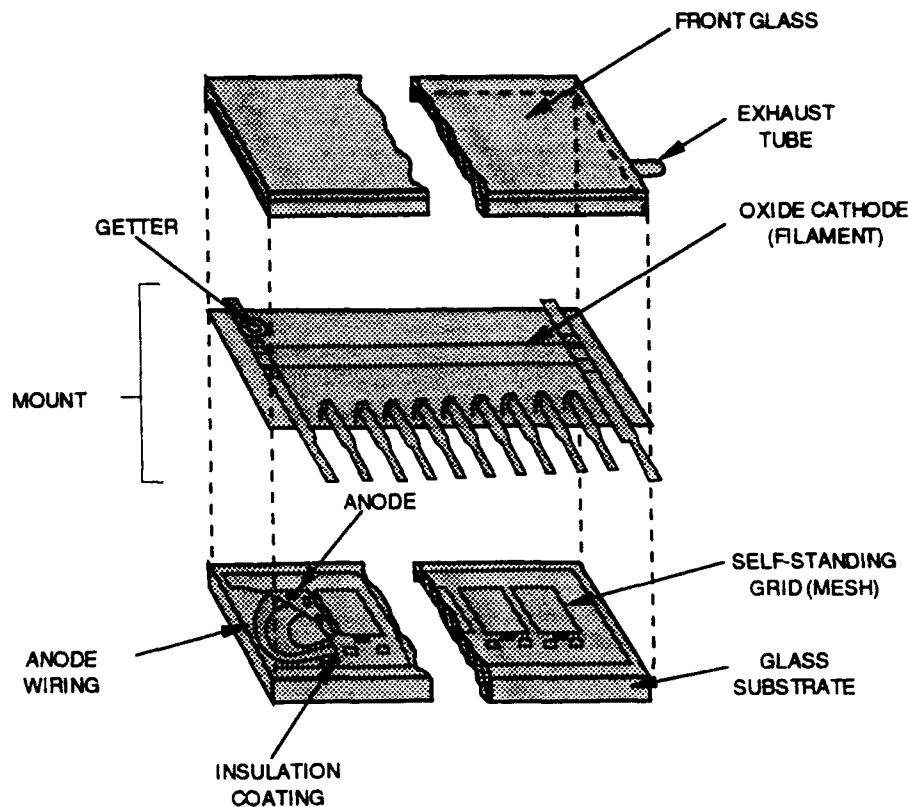


FIGURE 4.2-21. BASIC VACUUM FLORESCENT DISPLAY CONSTRUCTION
(Shinya 1992)

A VFD is a triode vacuum tube, containing a cathode, grid, and anode. The cathode consists of a heated tungsten wire. A low filament temperature is maintained so that the filament glow is not seen. The use of a grid in the construction of the display devices allows for easy control of display brightness. The anode consists of thin-film electrodes deposited on glass with phosphor material deposited on the electrodes.

The electrodes are deposited in a manner which forms the shape of the image to be displayed. These devices operate under vacuum and contain a getter to absorb impurities. Control of the electron current is accomplished by the simultaneous application of a pulsed voltage to the grid,

or to both the grid and anode of the desired elements. Images generated by this technology can range from a simple dot matrix character display to a complex display fabricated using photolithography.

VFDs have been in use in automobiles since 1976 and are being used in HUDs for automobiles, using higher luminance florescent material and a heat radiating plate for proper cooling.

4.2.12 Plasma Displays

The plasma, or gas discharge display takes advantage of the electrical breakdown of a gas when a sufficiently high voltage is applied to the electrodes which it surrounds. At this breakdown voltage, V_B , an avalanche phenomenon occurs, where a high current flows between the electrodes and produces photon emission. The amount of current which flows between the electrodes is limited by the series resistance of the circuit. When breakdown occurs, the discharge maintains itself unless the applied voltage is reduced below the level V_S , which is the sustain-voltage.

4.2.12.1 AC Plasma Displays

The plasma display can be either ac or dc operated. Figure 4.2-22 shows the structure of an ac plasma display panel.

The outside consists of two flat glass plates separated by a small distance. On each glass plate there are rows of conductors, the conductors of one plate being orthogonal to the conductors of the other plate. These conductors are insulated from the gas by a dielectric layer. The gas consists typically of a neon-argon mixture which emits an orange glow when excited. Display cells exist at the intersections of the rows and columns of conductors.

For normal operation, a positive and negative continuously pulsed sustaining voltage, similar to an ac waveform, is applied to all rows and columns. The positive and negative peaks do not exceed V_B . Hence, with only this signal applied, the display is blank. The gas in a particular cell discharges and emits light when a short duration pulse is generated in phase and exceeding the value of V_B , which is greater than the normally applied ac waveform.

When breakdown occurs in a particular cell, the dielectric on each side of the cell is rapidly charged by the ionized particles. The negative electrode receives a positive charge and the positive electrode receives a negative charge. Thus the cut-off voltage is rapidly attained and cell emission ceases. However, when the next half-cycle of the sustaining waveform occurs, the charge on the dielectric adds to the sustaining voltage and exceeds V_B , causing the cell to discharge continuously. Operated in this manner, the display exhibits a memory effect. An enabling pulse to a cell is in effect until a corresponding disable pulse is generated to deactivate the cell.

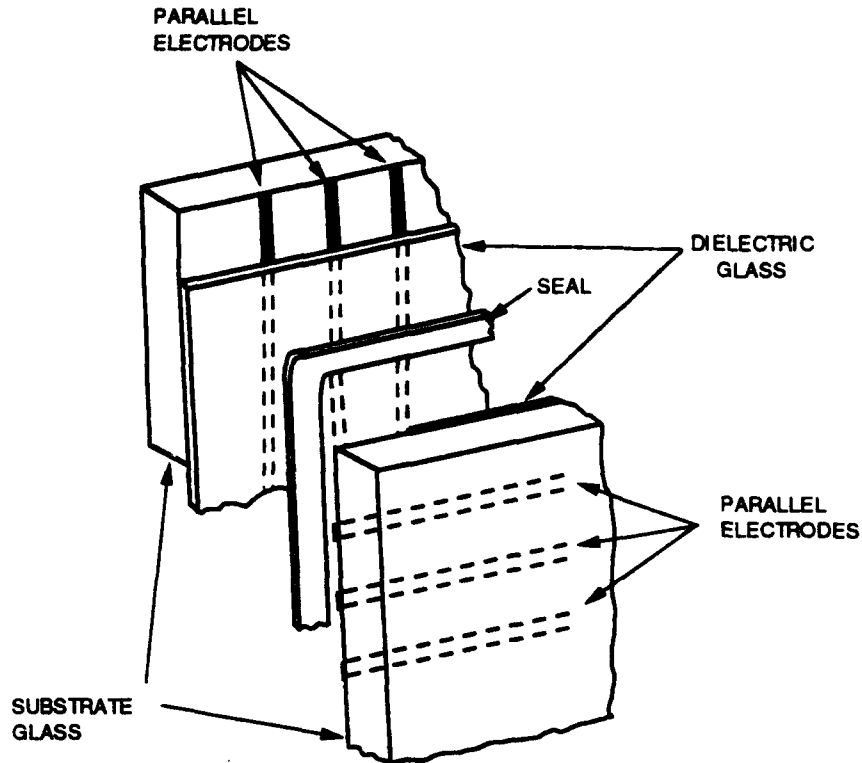


FIGURE 4.2-22. AC PLASMA DISPLAY PANEL STRUCTURE (Tannas 1985)

The ac plasma displays offer many desirable attributes such as:

- Thin panel production is possible,
- Long life under normal operation,
- Low failure rates,
- No flicker problems due to high frequency of sustaining voltage,
- Wide viewing angle,
- High resolution, and
- Good contrast.

There are drawbacks also to the use of this technology. Driving voltages in excess of 100 volts are required. The loads presented to the drive electronics are highly capacitive, generating high surge currents. The greatest drawback, however, is the relatively low luminous intensities the display generates. Readability in high ambient light, such as is found in cockpits, is an obstacle this technology has not overcome.

4.2.12.2 DC Plasma Displays

Dc plasma technology differs in several areas from ac plasma technology. The cell electrodes are in the gas and are not insulated by a dielectric layer. Normally, a stencil plate, with holes at the intersections of the row and column crossings, is added. This helps in the elimination of sputtering effects, which cause a thin metal film deposit, due to ion bombardment of the electrodes. These displays are normally operated with a pulsed dc voltage in the range of 150 to 200 volt (V) (Michel 1983).

In the plasma display there is a varying time delay from the application of the pulsed voltage to the establishment of a stable discharge. The dc plasma cell does not make use of the high frequency sustaining voltage as the ac plasma cell does. This causes a jitter effect that is particularly noticeable in the dc plasma cell. This effect is usually minimized by the introduction of priming cells in close proximity to the normal display cells. The priming cells introduce charged particles into the display cells before the application of the pulsed voltage and result in uniform ignition of the cell (Michel 1983).

The thickness of the dc plasma display is the same as the ac display. It is difficult to obtain high resolution displays using dc plasma due to problems such as crosstalk between adjacent cells. However, sharp images due to the fabrication technique, are characteristic of this technology. Hence, the commercial displays which use this technology are typically numeric, or alphanumeric.

The emission from the dc plasma display is a characteristic neon orange glow. The refresh rate of display panels using this technology needs to be chosen carefully to avoid the appearance of flicker.

Low temperature operation of this type of display should be avoided for devices containing mercury (Hg). The operating life will be impaired by low temperature operation for the device which uses Hg vapor in the gas mixture to avoid sputtering.

High voltage drivers are necessary for the dc plasma display as well. Varying the display intensity is accomplished by modulating the duty cycle of the high voltage drivers which perform the refresh. As with some of the other display technologies, a trade-off exists between the overall display brightness and the refresh method. If the duty cycle for each character is reduced to save on the overall supply current, then the display brightness is correspondingly reduced. This may happen if too many characters are refreshed in a particular scan cycle in order to reduce the driver hardware requirements.

4.2.13 Display Applications

4.2.13.1 Head-Down Display

The HDD is the primary type of display used on modern commercial transport aircraft. It is generally a direct view, computer driven CRT display with capabilities for graphic and video images. HDDs are normally designated to have a single function, such as display of primary flight data or weather radar data, but with the throw of a switch, data on the displays can be swapped around. This allows for maintaining the PFD data in case the normal display CRT malfunctions.

Examples of HDDs for various commercial transports are seen in section 2. Modern transports such as the Airbus 320 and McDonnell-Douglas MD-11 use multiple CRTs across the cockpit, replacing older electromechanical indicators. Older aircraft are often upgraded with glass cockpits along with the removal of a number of the electromechanical indicators.

4.2.13.2 Head-Up Display

SAE ARP4102/8 states "HUD systems shall provide the pilot with a display that enables him to assess aircraft attitude and flight path in relation to and in association with external visual cues." The primary use of the HUD is to aid the pilot during approach, landing, and takeoff. This is done by projecting the primary flight information on the windshield, giving the pilot access to this information without a need to look down in the cockpit during this critical time. The familiar "T" arrangement should be used as the basic data format. A HUD is a valuable display, especially during times of low visibility when the pilot is seeking visual contact with the ground.

The HUD is becoming increasingly common in commercial transport aircraft. Some modern transports are manufactured with HUD systems while some older aircraft have been retrofit with this device.

According to Agneessens (1988) optical systems used in airborne applications are classified according to their functions. These functions are:

- Rejection or minimization of unwanted light which will confuse the view of the display. Sunlight rejection is the usual requirement and is frequently accomplished by the use of filters.
- Magnification and/or collimation. The plane of the object lies at the display device and an optical system positions the image at a convenient distance from the viewer.
- Combining two or more separately generated images.
- Superimposing a display image over a direct view of the outside world.

The HUD is a particular application of a cockpit display technology which serves to enhance the information availability to the pilot without the pilot having to look down at a particular display for information. It generally utilizes all four of the functions listed above. It is essentially a derivative of the optical gunsight, where the gunsight is replaced by a CRT-, LC-, or LED-generated image. The gunsight had an illuminated reticle or crosshairs which was reflected from a combiner placed in the line of sight of the pilot. This sight was focused at optical infinity so that aiming accuracy was increased. When an image is focused at optical infinity it appears to be at the same distance from the observer as objects that are beyond the image.

The basic components of the HUD are shown in figure 4.2-23. The CRT generates the image to be displayed. It is then projected through a relay lens to the fold mirror, which is used to redirect the optical path. A collimating lens focuses the image at optical infinity. The combiner serves to combine the optical images in front of the pilot's eyes. The combiner is made in such a way that it reflects the particular wavelength of light generated by the CRT while other wavelengths pass through it. Also, the scene outside the cockpit passes through the combiner. Since the combiner is partially composed of an organic material, it needs to be protected from exposure to high temperatures (Spitzer 1987).

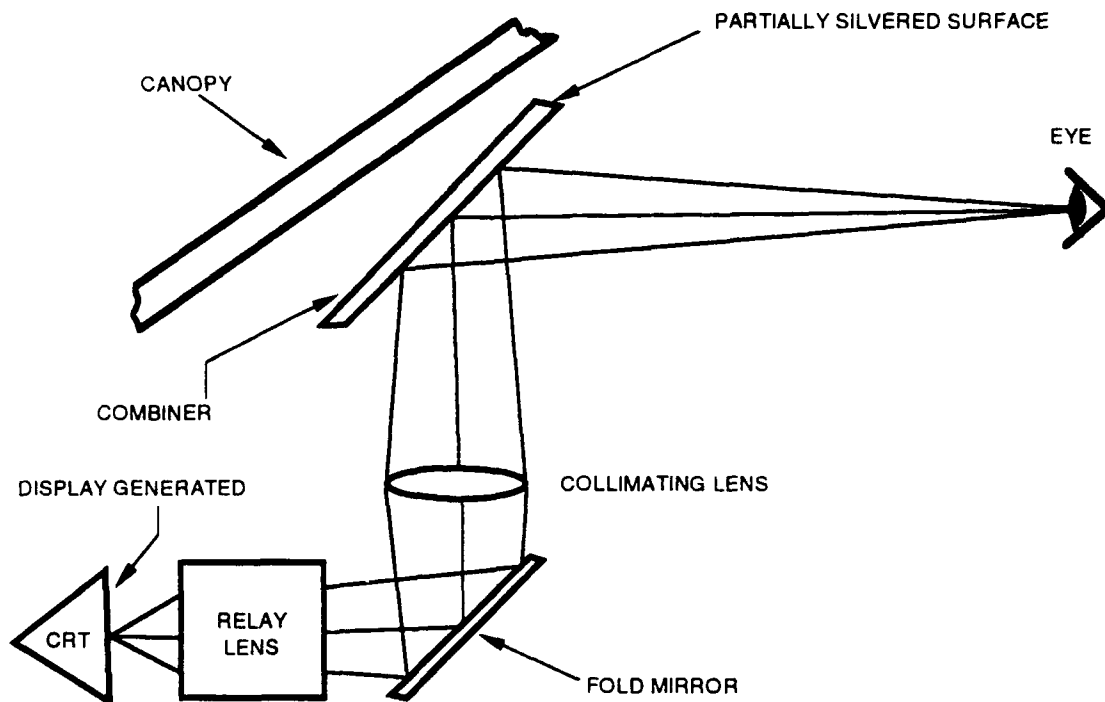


FIGURE 4.2-23. BASIC HUD COMPONENTS (Pinkus and Task 1988)

HUDs may also be built using three elements in the combiner system. These would be the upper combiner element, the forward combiner element, and the rear combiner element. The upper and rear combiner elements serve as reflectors for the CRT image and the forward element is the image collimator. Advantages of the three element system over the single element are (Spitzer 1987):

- Better producibility,
- Simpler overall HUD system design,
- Freedom from secondary reflections, and
- Larger FOV.

4.2.13.3 Head-Up Display Failures

SAE ARP4102/8 specifies that the probability of hazardous or misleading information being presented by the HUD without warning or blanking should be extremely remote. Displayed parameters that lose their validity should be removed from the display by the controlling software. In addition any failure of system computation or monitors should result in the complete blanking of the display, along with annunciation of this fact.

4.2.13.4 Head-Level Display

A product which uses a combination of a HUD and a Head-Level Display (HLD) in a single package has been developed by Sextant Avionique. The HLD is mounted directly below and in line with the HUD. It is a collimated display to allow easy transition between the HUD and HLD.

The HLD presents more information to the pilot by displaying HUD related or synthetic images. It has the potential of eliminating HUD clutter by a splitting of information between the two displays. This device is intended for use in military cockpits where the demand for large amounts of information in a short period of time is a normal requirement.

4.2.13.5 Other Cockpit Displays

The Helmet Mounted System finds application mainly with the military, but also may be used in civil work by police or border patrol officials. Helmet mounted systems are used for both sights and displays. The Helmet Mounted Sight (HMS) is used to align a weapon delivery system with the target focused on by the HMS. Various sensors are used to measure the angle and position of the helmet and this information is then fed to the weapon aiming system. A system such as the HMS allows for the acquisition of target information which is outside the normal field of view of the HUD.

The HMD uses helmet position sensors, but also contains a miniature high resolution CRT display and optics. With the HMD a synthetic image can be presented along with sighting information. Mounted near the eye, the image is collimated to appear at optical infinity. One of the concerns over the use of the HMD is the weight of the CRT and optics. Another is the adjustment of optics for different users of the HMD.

NVGs are worn by pilots flying night missions and are attached to the helmet. A visible phosphor screen image is presented to the pilot by an imaging system to enhance the pilot's night vision ability. This is done by the aid of sensors that respond to IR emissions. This system tracks with the head movement of the pilot and displays real time images.

Compatibility with cockpit displays is a primary concern of NVG. EL, LED, and other displays in the cockpit emit IR at a relatively high intensity compared to that which is outside the cockpit. IR filters are used on cockpit displays and indicators so that the pilot can view them while wearing NVGs.

4.3 Voice Technology

Speech is the most natural form of communication. The primary intent for the use of speech technology in the cockpit is a reduction in workload for the pilot of high performance aircraft. When used as a control device it frees the hands and eyes for other tasks. This technology has been viewed as a possible solution to the problems associated with having too many displays and indicators, and too many visual and manual tasks to perform in the cockpit. It has been under consideration for years, particularly for use in rotorcraft, where the pilot needs both hands to fly. Commercial cockpits may take advantage of voice technology for voice warnings, way point announcements, checklists, and other status messages.

Voice interactive systems are defined as "the interface between a cooperative human and a machine, which involves the recognition, understanding or synthesis of speech, to accomplish a task of command, control, or communications, and which involves feedback from the listener to the speaker (Beek and Vonusa 1983)." The voice interactive system has been the focus of extensive research work and involves not only the synthesis of speech, but also speech recognition. It is the latter technology which remains to be perfected before reliable and convenient use can be made of this technology in the cockpit. Table 4.2-7 lists some of the advantages of speech technology.

Some of the disadvantages of speech technology are:

- Various physical conditions can alter speech characteristics.
- Other audio range emissions can interfere with the desired source.
- Various psychological conditions can alter speech characteristics.

- Speech synthesis may interfere with other aural indicators.

TABLE 4.2-7 SPEECH TECHNOLOGY ADVANTAGES

Engineering
<ul style="list-style-type: none"> • Can be more accurate. • Can reduce manpower requirements. • Can be a cost-effective man-machine interface.
Psychological
<ul style="list-style-type: none"> • Most natural form of communication. • Can contain information regarding emotional state of speaker. • Can reduce visual information overload and workload.
Physiological
<ul style="list-style-type: none"> • Permits operator mobility. • Does not require line of sight with device. • Works in completely dark environment. • Frees eyes and hands for other tasks.

4.3.1 Voice Synthesis

Humans produce sound when air from the trachea passes by the vocal cords. The sounds are modified by the cavities of the throat, mouth, and nose, which act as audio filters and therefore determine the waveform of the produced sound. Speech generating hardware should model these characteristics faithfully to produce speech that sounds human, rather than poor quality, mechanical sounding speech.

There are three methods for digital speech generation. They are:

- Digitized speech,
- Synthesized, word generated,
- Synthesized, phoneme generated.

Digitized speech is reproduced from a digitally recorded voice. If the input is sampled at a sufficiently high rate, then the voice that is reproduced will sound very natural. A problem with this technique is that large amounts of memory are required to store the digitized speech.

Another form of digital speech generation is synthesized, word generated speech. This technique uses a compressed pattern produced from the original speech input. This method inherently introduces some distortion in the reproduced signal, and sound reproduction is less natural. The amount of compression applied to the input speech generally determines the amount of distortion in the reproduced waveform.

The last method of digital speech generation is synthesized, phoneme generated speech. Phonemes are the smallest elements of speech. Combinations of phonemes are put together to form any word of our vocabulary. Since the number of phonemes used to represent the set of different sounds is small, the amount of digital memory used for speech generation is not a problem.

Speech is generated from text messages which exist in memory in a table format. The messages are pre-programmed sequences of phonemes which are combined to form words. Each byte from a particular selected table is presented to the phoneme generator in sequence. The generator then produces the sound associated with the bit pattern, adding the element of time to the sound. Another method used in phoneme generated speech is the application of pronunciation rules to text. The desired text is first analyzed and decomposed into the corresponding phonemes. These phonemes are then presented in sequence to the speech generator circuit.

Voice alert messages may be used in the cockpit as part of the FAS in cases where there is a serious system failure or the aircraft is in a hazardous configuration. SAE ARP4102/4 states that voice may be used as a supplement to the attention aural alert and the associated visual display. The voice alert message should:

- Be easily distinguishable from ordinary communication.
- Consist of short phrases for ease of recognition.
- Be consistent with other visual indicators.
- Use common terminology.

4.3.2 Voice Input

Variations exist in the voice characteristics from one person to the next. In order for voice recognition to work more efficiently, "training" of the computer with the user's voice is generally required. This training involves presenting each word to the voice recognition circuit a number of times. The Central Processing Unit (CPU) then converts the voice input into a transformed digital word and stores the pattern in memory. The computer averages the waveforms from the

multiple samples of collected words and uses these averages as the basis of recognition during normal operation.

A word to be recognized is compared with the set of pre-stored reference words called a template. After the compare, the result is picked by the closest pattern found in the template. If the pattern is not sufficiently close to the template, the word will be rejected. Variations in normal speech are significant so that rejection is common. Best results are obtained if the creation of the template is performed immediately before use and in the same operational environment.

Another problem to be handled with voice recognition is the time duration differences of the same spoken word. Spoken words are rarely the same in duration and the recognition hardware needs to deal with this. A typical solution to this problem is to normalize each digital word pattern so that it is the same length as all the others. Patterns are lengthened or shortened, either linearly or nonlinearly, to correspond to the standard length word.

There are many difficulties to overcome when dealing with voice recognition. Since the generation of a template is required for words in the system, programming time in the normal operating environment is required. Psychological stress of the user causes errors in recognition. The operating environment is often full of extraneous noises. This is particularly true for the cockpit. A reduction in acoustic noise may be required before the recognition circuit performs properly.

Other difficulties are encountered in voice recognition. Since speech is continuous, there may be no clearly defined boundaries between spoken words. The recognizer needs to be able to pick out the individual words or else the speaker needs to modify the normal manner of speaking by distinctly pausing between each spoken word. Ambiguity can be a problem, since there is no acoustic difference between some words, such as "to" and "two". Words need to be interpreted in their context or the vocabulary carefully chosen and limited. Voice recognizers must not only recognize the correct words, but also must reject the incorrect ones.

The percent of correct words for a word recognition device is an important rating for a voice recognition system. Any input errors, which may be caused by the recognition device or the operator, require a method of correction. Feedback of the matched word can be performed using an alphanumeric display device to ensure proper entry. If an incorrect word is displayed, then the system user needs to be able to also reject that word by voice command.

Voice input is not viewed as a viable method of aircraft systems control for the modern commercial transport. Improvements are necessary in the areas of phonetic accuracy, vocabulary size, response time of the recognition system, and performance in high noise environments. In addition, other human factors issues associated with the use of voice technology in the cockpit need to be addressed.

4.3.3 Voice Technology Applications

The designer's task for a voice synthesis system is greatly simplified by the availability of Large Scale Integration (LSI). Manufacturers produce LSI devices that contain the many functions required for generation of high fidelity speech. Single LSI devices, such as the Texas Instruments TSP50C14 IC, contain the following functions:

- General purpose CPU,
- Digital filters,
- Read-Only-Memory (ROM),
- Clock oscillator,
- Digital/Analog converter, and
- Audio amplifier.

Systems that include voice synthesis in the commercial cockpit include the Ground Proximity Warning as well as a checklist management system. Heads Up Technologies manufactures a digital speech annunciator which combines synthetically generated audio with an annunciator panel. It also can be connected as a closed loop system to certain critical systems for checking take-off configuration, giving an aural warning if not correct. This particular device is planned for use on the Citation jet and is used in certain military aircraft such as the C-130.

4.4 Keyboard Technology

Prior to the introduction of the keyboard into the cockpit, the interface to the numerous avionic systems was through discrete dials and switches. When the number of dials and switches grew beyond what was deemed reasonable, keyboards were introduced. The keyboard is now the normal method of interacting with modern and complex digital avionic systems. For this reason, keyboards are ubiquitous in modern transport cockpits. Other input devices such as discrete knobs and switches are used in the cockpit. Capacitive touch pads and trackballs will appear in the future.

The current keyboard designs for cockpit use are driven largely by the availability of cockpit real estate. Many avionic systems require programming by the flight crew. These considerations have given rise to the MCDU.

The MCDU consists of an alphanumeric keypad, with a multiple line display in a self-contained package which typically mounts on the pedestal. The display is normally a monochrome CRT, although AM LC displays are used in some military MCDUs. In addition, the MCDU contains a data bus interface and all the computing power necessary for performing the display, data bus,

and other MCDU associated computational tasks. The data bus interface typically uses the ARINC 429 for commercial and the MIL-STD-1553 for military applications. Current MCDUs may contain high speed 32-bit processors with memory in the order of megabytes.

In the MCDU, the keys consist of mechanical buttons connected to electrical switches. In the button itself, a display may be fabricated, using some display technology such as an LED or LC dot matrix array. This array, and hence the key function via software, can change based on the current flight phase or based on input from the aircrew (Spitzer 1987).

CRTs may also fill the purpose of the MCDU by the use of bezel mounted switches around the face of the CRT. The function of these keys is also alterable by software. Another method is to display the switch button as part of the CRT display and use some form of touch input technology over the CRT face to replace the mechanical switch input.

The physical keys of a typical keyboard are matrix scanned by digital logic. Since the keypad represents a matrix of switches, a CPU drives one row on one side of the matrix to a fixed logic state using digital driver logic. At the same time, the other side is read through an input port. A change of the normal logic state indicates the depression of a key. Rows are scanned sequentially until the process is completed and then it starts over again. Software debounces the key stroke and marks the starting and ending point of the key depression.

Keyboard displays must also be compatible with night flying. Displays using LEDs need to be able to decrease luminous output uniformly to a level that will accommodate the requirements for low light conditions. The use of LC displays requires that backlighting be used during low light conditions. The backlighting needs to be barely visible for night flying and very intense for daylight viewing in sunlight.

One of the major drawbacks of the use of keyboards is the data entry problem. Keyboard entry errors are common. Fluctuations in workload, turbulence conditions, variable lighting conditions, and other factors demand that keyboard entries be easily verified. Verification is necessary so that the data entered is the data which was intended. A display is used with the MCDU to show the data entered through the keyboard and allow for verification and correction if required. Entries should be both made and checked carefully by the user and the MCDU designer should facilitate this task by using high resolution displays along with a well-thought-out keyboard design.

Ergonomic considerations receive a great amount of attention where keyboards are concerned. Key size and key separation are important design issues for eliminating input errors. Physical keyboard parameters are varied by designers in an attempt to reduce the number of input errors. The accuracy of keyboard input is influenced by many physical factors in the keypad design, such as:

- Key separation distance,

- Use of barriers between keys,
- Amount of key recessing, and
- Amount of key resistance (key click operation).

The following are general guidelines for MCDU design.

- Separating the alpha and numeric keys by using outlining around key groups and grouping keys according to function.
- Using shape coding for key groups (numeric keys: round; alpha keys: square).
- Avoiding keys with more than one function,
- Clearly displaying current mode of keyboard when MCDUs are used.

An example of a system using an MCDU is the Collins FMS-800 Flight Management System, which uses the MCDU as the primary crew control interface. The MCDU integrates the functions of communication, navigation, Identification Friend or Foe (IFF) control, GPS/INS navigation, flight instruments and controls, autopilot, stores, and radar. Multiple interfaces, such as MIL-STD-1553, ARINC 429, and analog, are included for interface versatility.

5. HUMAN FACTORS AND THE PILOT-VEHICLE INTERFACE

5.1 Introduction

5.1.1 Human Factors and the Pilot-Vehicle Interface

Human Factors and the PVI considers the capabilities of pilot performance in relation to the design of the cockpit environment. The task of designing digital systems for the cockpit is monumental. Adding the pilot to this environment presents an important factor for designers to consider. The capabilities, limitations, and physical stereotypes of the pilot population must be incorporated into the system design. The design of the PVI must consider human factors such as the effects of automation on the cockpit environment. The designer must appraise the role of the pilot in an automated cockpit and determine which tasks are best automated and which should be the pilot's responsibility. Systems design must consider the way in which the pilot perceives the cockpit environment. The designer must determine how information is best presented and organized.

The pilot's job is complex. Constant awareness of the aircraft's status is required. The designer must be conscious of the pilot's workload limitations. He must ascertain how much the pilot can perform safely and under what conditions. Digital avionic systems are intricate. The pilot must receive training to operate these systems safely. In addition to training for the safe operation of the aircraft, the pilot must be able to communicate and interact with the flightcrew and with ATC.

At the heart of human factors and the PVI is safety. Understanding the capabilities and limitations of the pilot can help designers create systems that can be used knowledgeably and safely by the pilot and crew. While the safety record of commercial airlines is admirable, anecdotes of incidents and accidents reported anonymously by pilots and flight crew reveal areas in which improvement is imperative.

Although a considerable amount of information is known about how pilots interface with their aircraft, a great deal remains to be discovered. This document examines a number of human factors issues related to the PVI. Research germane to these areas is presented and issues are raised. One valuable resource to for this endeavor has been the FAA National Plan for Aviation Human Factors.

5.1.2 The National Plan for Aviation Human Factors

In November 1988 the U.S. Congress enacted "The Aviation Safety Research Act of 1988" (Public Law 100-591). This law directs the FAA to augment its research efforts in human factors and to coordinate its efforts with those of NASA. The National Plan for Aviation Human Factors represents the first step of an intensive effort to coordinate human factors-related research in aviation.

The purpose of the National Plan is:

- To identify the technical efforts necessary to address the most operationally significant human performance issues in aviation and acquire the resources necessary to fund these efforts,
- To allocate resources efficiently by coordinating research programs at various government laboratories,
- To communicate research needs to academic and industrial "centers of excellence," and
- To promote the means by which human factors knowledge is transferred to Government and industry.

The objectives of the plan are:

- To encourage the development of principles of "human-centered" automation and the design of advanced technology that will capitalize upon the relative strengths of humans and machines,
- To improve aviation system monitoring capability, with an emphasis upon human performance factors,
- To encourage the improvement of basic scientific knowledge and facilitate understanding of the factors, both positive and negative, that significantly influence human performance in aviation,
- To develop better techniques for the assessment of human performance in the aviation system,
- To determine the most effective means of air-ground information transfer in the National Airspace System,
- To encourage the development of controls, displays, and workstations for aviation application that facilitates the interface between humans and machines,
- To develop enhanced methods of training and selection for aviation system personnel,
- To develop human factors-oriented validation and certification standards for aviation system hardware and personnel that will enhance both safety and efficiency.

The National Plan has been a major resource for identifying human factors issues and problems concerning human factors and the PVI.

5.1.3 Scope and Organization

The field of human factors in aviation is broad. Although the pilot interacts with the crew, the systems, the aircraft, and the airspace environment, the major focus of this report is on the pilot and the cockpit interface. Of necessity, the scope of this section is limited to the relationship between the PVI and:

- Safety,
- Cockpit Automation,
- Design Issues,
- Crew Workload, and
- Crew Resource Management (CRM), and Training.

For each area, an overview of significant research findings will be presented. This information is culled from representative current studies, professional journal articles, conference proceedings, textbooks, government documents, interviews with experts in the field, and incident and accident reports. At the conclusion of each section, a list of issues and questions from the National Plan for Aviation Human Factors is presented.

5.2 Safety and the Pilot-Vehicle Interface

5.2.1 Factors Contributing to Aviation Safety

New procedures based on research and accident investigation as well as improved technology have contributed to aviation safety. Accidents, especially those involving human error, usually are associated with a chain of events. Four fundamental accident-prevention measures are (Diehl 1991):

- Eliminate hazards and risks; for example, by enforcing strict accident prevention measures.
- Incorporate safety features; for example, by standardizing location of cockpit controls, and using bird collision-resistant windscreens and canopies.
- Provide warning devices; for example, Ground Proximity Warning System.

- Establish procedural safeguards; for example, checklists, Standard Operating Procedures (SOPs), personnel selection standards, and training programs.

The "Sterile Cockpit Rule" was promoted by the FAA to reduce incidents that result from distractions occurring in the cockpit during critical phases of flight below 10,000 feet. FAR 121.542(b) and FAR 135.100(b) state that "No flight crew member may engage in, nor may any pilot in command permit, any activity during a critical phase of flight which could distract any flight crew member from the performance of his or her duties or which could interfere in any way with the proper conduct of those duties."

Based on a study derived from reports from NASA's Aviation Safety Reporting System (ASRS), distraction incidents have continued to occur since this rule was announced (Barnes and Monan 1990).

Within the aircraft, new technology can contribute to aircraft safety. Warning and alerting system computers can incorporate intelligent systems which can analyze problems, prioritize alerts, and offer solutions or probabilistic diagnoses. The Airbus A320 and Boeing 747-400 display system schematics for diagnosis and intervention. The Electronic Library System (ELS) for the Boeing 777 will allow the pilot electronic access information that formerly was spread among paper charts, manuals, procedure books, and passenger manifests.

Another technology-driven safety factor is error-evident displays. The map mode of the HSI of the Boeing 757/767, Airbus A310/320, and McDonnell-Douglas MD-88 clearly displays lateral navigation errors.

Predictive systems can contribute to aviation safety. These system use forecasting algorithms to predict trouble before alarm conditions are reached. The crew is informed of the impending alarm condition (Wiener 1989).

5.2.2 Factors Contributing to Aviation Incidents and Accidents

Despite advances in technology, training, and regulations, there are still many factors contributing to aviation incidents and accidents. Among these factors are (O'Hare and Roscoe 1990):

- Lack of response to warning systems,
- Overreliance on automated systems,
- Chart reading errors,
- Communication errors,
- Diffusion of responsibility,

- Crew monitoring failures.
- Inadequate training.
- Poor judgement and decision making.
- Copilot unassertiveness, and
- Peer pressure.

Wiener (1989) has identified several additional factors:

- Automation — Automation reduces the capacity for small errors while creating the potential for large ones.
- Design — Nonstandard controls, non-communicative displays, overly complex systems, illogical systems, keyboards in proximity to one another with different layouts, and keying errors are common causes of accidents and incidents.
- Communication — Accessing information through keyboards and screens makes it more difficult for two pilots to check each others' inputs.

The National Transportation Safety Board (NTSB) indicated that although the technology and reliability of automated systems are impressive and have benefitted the airlines, "what is missing are principles, rules, and guidelines defining the relationships between that technology and the humans who must operate it" (Phillips 1992).

5.2.3 Safety and Situational Awareness

Maintaining situational awareness is crucial to aircraft safety. Although one goal of automation is to help the pilot maintain situational awareness, automation also is cited as a major cause of accidents and incidents. Problems can result from inappropriate application of automation technologies either by the designer or the user, rather than from "overautomation."

Users frequently do not understand the intended application of the system while designers may ignore the need for feedback about system status. Because of the complexity and size of modern commercial transport airplanes, crews are often physically and mentally isolated from the systems. Mental isolation caused by lack of feedback is one of the major contributors to reduced situational awareness (Braune 1990).

There are critical phases of flight during which situational awareness is especially crucial. Schwartz (1987) describes a safety window as a block of airspace centered around a runway and extending from the ground to 2,000 feet above ground level.

The window is six to eight minutes long when flown in a conventional turboprop or turbojet aircraft. Roughly 80 percent of the accidents involving professional pilots occur within this window. Most accidents taking place in this window can be termed generic; they are not specific to a particular type of aircraft. It is interesting to note that workload intensity peaks during flight within the safety window.

During all phases of flight, but especially within the safety window, high situational awareness yields lower mishap potential. The more pilots know about what is going on around them, the safer they are likely to be.

Loss of situational awareness may occur as a result of a chain of events, or an error chain. The error chain is a concept that describes human error accidents as being made up of a series of errors. Links are identifiable by means of specific clues. By breaking any one link a flight crew potentially can break the chain and prevent an accident. Analysis of a number of accidents indicates that at least five clues are present and identifiable in most human error accidents. Links in an error chain tend to occur sequentially, may or may not be related to each other, and may not be readily visible to the crew. Clues to loss of situational awareness include:

- Ambiguity — two or more independent sources of information differ,
- Fixation or preoccupation — focus of attention on any one item or event to the exclusion of all others,
- Confusion — a sense of uncertainty or anxiety about a particular situation — falling behind the aircraft,
- No one in control of the aircraft,
- No one looking out of the window,
- Use of an undocumented procedure,
- Violating minimums,
- Failure to meet targets, and
- Departure from SOPs.

Wiener (1990) comments that barriers to situational awareness in the cockpit include complacency and pilots "falling out of the loop." Strategies to prevent this are training for wise use of the equipment and installing error-evident displays.

Post-accident investigations reveal that human-human and human-machine communication fails to convey an accurate and timely picture of the situation. For human-human communication,

Training for crew and all persons in the system is one intervention strategy. Intervention for human-machine problems include design improvements ranging from traditional human factors to implementation of intelligent communication systems. Often government's and management's role in promoting situational awareness is concealed in accident investigations by focusing on the last person in the causal chain: the pilot. Intervention strategies include better governmental regulations and total quality management of flight operations.

5.2.4 Digital Systems/Aircraft Incidents, Accidents, and Lessons Learned

Through accident and incident investigation, information can be gained to increase aviation safety. Digital systems/cockpits present new investigation requirements. Automated cockpits are changing the types of data needed to perform accident investigation work. Some proposed changes include the addition of video recorders on the flight deck to tape what the electronic displays are showing pilots, and more parameters to be stored in flight data recorders. Investigators need input and output of data to and from the flight management computer (Hughes 1992).

A number of agencies investigate aircraft accidents and incidents, and publish reports. In the United States, the NTSB maintains overall responsibility for reviewing and reporting the facts that surround major civil aviation accidents and incidents. The ASRS, developed by NASA, focuses upon human performance-oriented incident investigation. Aircrews, air traffic controllers, and others can file reports with this agency. Reports remain confidential and the reporter is immune from prosecution in cases other than those involving some criminal act (Wiener and Nagel, 1988). The FAA sponsors an Aviation Safety Hotline. Reports to the hotline remain confidential and callers are protected from disclosure under the provisions of the Freedom of Information Act. The Civil Aviation Authority (CAA), United Kingdom's aviation regulatory authority, investigates aircraft accidents and incidents, and produces reports similar to those of the NTSB. In addition to these sources, other agencies sponsored by governments and industries throughout the world investigate aircraft accidents.

ASRS reports contain a wealth of information about human factors and the PVI. The reporters not only explain the details of the aviation safety incidents, they also explain why the incident occurred, and sometimes lessons learned by the reporter.

A request was made to the ASRS for reports referencing advanced cockpit flight guidance systems involving two engine, advanced cockpit, widebody (over 300,000 pounds) aircraft. The request yielded 55 reports from March, 1986 through November, 1991.

While FMSs can offer savings in time, cost, and workload, they also present an opportunity to introduce error into the system. Data entry problems, FMS database, and FMS software problems were mentioned in nearly a third of the reports. Many of the problems were the result of keying mistakes.

A training issue raised at the FAA's Cockpit Electronic Display Workshop: Cockpit Human Factors Program (April 7-9, 1992) and echoed in the Human Factors automation literature was determining conditions under which the pilot should transition from an automatic system to flying the airplane manually. The incident reports include flight crew statements that indicate preoccupation with the systems or a reluctance to switch to manual mode. Reporters made statements such as, "becoming 'mesmerized' by the computer programming," becoming "absorbed in determining which flight instruments are reliable," "dwelling on each previous event caused a preoccupation that caused the next," "relied too much on the Flight Management Computers (FMCs) in a situation where they require too much input and monitoring and increase the workload," "was trying to set up the approach as well as fly the aircraft," and "pilots quit using their brain and get too engrossed in the computers." In over one third of the reports, failure to switch from an automated system to manual mode was among the causes of the incident.

While flight deck automation strives to reduce flight crew workload, many incidents were related to workload. Some typical comments include:

- "On a two-man high performance aircraft, automation is supposed to relieve the pilots of a high workload, but when even minor problems occur, one's attention can be greatly diverted. I believe that in our present day two-man aircraft, one pilot is routinely taken out of the loop by even ordinary changes necessary in our high density environment."
- "Though they [computers] are designed to reduce crew workload, I feel in many instances, they do just the opposite. In high traffic areas with constant altitude and airspeed adjustments, the VMCSs [sic] should not be used."
- "...we did not fly the airplane first and program the FMC second, we relied too much on the FMCs in a situation where they require too much input and monitoring and increase the workload."
- "In a two pilot environment in which what was formerly the second officer/flight engineer's functions are now totally automated, an apparent failure of the automation is particularly distracting to the captain and first officer. The crew member flying becomes immediately absorbed in determining which flight instruments are reliable while the remaining crew member seeks the source of the problem. This results in a brief interval when the heading and altitude are of secondary concern. Stabilized flight is first. ...A two pilot crew concept works great, but only as long as the automatic black box items which have replaced the second officer are feeding the captain and first officer accurate information."
- "...I was so busy watching for traffic, monitoring our departure, trying to sort out electrical/electronic problems, talk on the radio, realize my error, safely correct it, watch for reported traffic, climb, etc., that by the time I was ready to tell them about our problems, they were already giving the phone number...A two-man cockpit on a short leg in a widebody with electronic problems is too busy."

- "Though the FMS and associated capabilities greatly reduce workload when parameters can be preprogrammed or easily entered and executed, sometimes it is not the most expeditious way to carry out a task."
- "These two-man cockpits have become so complex that reducing the workload means four or five separate functions to get the airplane turned to an outer marker."
- Trying to utilize all the magic of the widebody while inexperienced in the widebody led to me being behind the airplane during the crucial approach phase."

Inadequate situational awareness can occur through lack of vigilance, complacency, and over-reliance on automated systems. The incident reports reflect this in the frequent use of statements such as the reporter was unsure of why a particular event occurred. Other statements report reasons such as:

- "I don't know why, with everything apparently set in properly, the aircraft did not descend at the proper time. I feel the cause of this mistake is too much reliance on automated systems and a lack of vigilance on my part as to the altitude and position of my aircraft."
- "I still don't know what the problem was...This whole incident probably would not have happened if I had been more observant of the Flight Mode Annunciator (FMA) indications."
- "The captain and myself analyzed the event noting two main points: The FMC was properly programmed and appeared to be functioning normally, and the captain and myself should have been cross-checking VOR raw data with the FMS descent profile. This incident demonstrates the limitations of an 'electronic cockpit.'" Basic flying skills should not be forgotten."

Training concerns were revealed through the report narratives. Reporters mentioned areas that received little attention or were not taught at all:

- "We were attempting to utilize the new full up features of the FMC, but neither of us were proficient in its use. Nor had we been given any hands on training on the new features."
- "...Lack of complete knowledge of the autoflight capabilities and vagaries led to a nonstandard and ultimately unsatisfactory flight procedure."
- "These two-man cockpits have become so complex. ...Perhaps we need more training, or at least an inoperable components training."

- "Contributing to this incident is the fact that the international ground school can lead you to believe that the aircraft has three long range navigation systems, when in fact you only have two. Three IRS and 1 FMC = 1 long range nav system. Those same 3 IRSs and the other FMC = the other long range nav system. Failure of either FMC brings you down to one long range nav system. This is not emphasized in ground schools as we are so used to flying with 3 INS, or Omega systems, I am going to recommend that this be emphasized in the schools."
- "We've since determined that with a profile descent selected like we did and an altitude above the Touch Down Zone Elevation (TDZE) set in, if the profile is reselected all restrictions on the profile in addition to the one added above the TDZE will be reinstated. Thus the computer/airplane will comply with the restrictions on the profile even if the altitude in ADW is set to 0'. Unfortunately none of this was taught in ground school."

Interaction, communication, and a clear delineation of tasks among crew members, CRM, has been shown to affect flight safety. A number of reporters cited problems in this area.

- "Captain did not encourage participation of the Pilot Not Flying (PNF). When it was his leg, he did not like suggestions on how to do his job; copilot had been conditioned by flying with this captain all month. Was not as vigilant as he should have been."
- "I attempted to explain to the first officer once we were parked at the gate that he had configured the aircraft improperly. Unfortunately he was not receptive to my input and elected to ignore my cautions. Contributing factors: ...Crew coordination, recently merged seniority list placed junior/younger captain with older first officer and created uncooperative atmosphere."
- "First officer had failed to complete setting up the FMS and was depending on it to do the navigating."
- "As for my part, all of this comes from one thing. I wasn't watching the captain. Unfortunately, the fact is that I often don't. ...But most of all, our system of crosschecks will work if a strict discipline is followed, especially when one thing goes wrong, others will follow."
- "My recommendations to my fellow pilots flying new, high performance aircraft: Conduct a detailed pre-departure briefing with the captain when flying an unfamiliar procedure. Discuss how the procedure is to be flown, and what nav instruments will be used. Do not be rushed before takeoff!!! Take a delay and talk it out. ..."
- "Contributing to this incident were several interruptions of our cockpit routine by the complaining number one flight attendant."

- "Because of my inexperience on type the captain was unwilling to listen to any suggestions from me. ...I should have been more forceful with my suggestions instead of just repeating them."
- "How did this happen? I suppose the wizardry of the 'glass cockpit' and two newcomers who were not aggressive enough intervening when the computers did other than what they expected."

Fatigue and scheduling procedures were contributing factors to several incidents. One reporter noted, "Probably the most important cause of this incident was a XA00 [sic] AM get up after a fitful few hours of sleep. I've noticed that most everyone starting a physical/mental task get a chance to warm up (baseball pitchers, golfers, etc. — even a simulator session starts with a few steep turns). I believe the bottom line was that I wasn't mentally ready to go flying. We spend millions on hardware for safety, but the crew schedulers are still just filling the squares regardless of one's body clock." In another incident the reporter was fatigued and repeatedly made mistakes while trying to program the FMS. Again, poor airline scheduling procedures were cited.

Equipment malfunctions were mentioned in the reports, especially pertaining to the flight management system. However, some incidents may be attributed to the pilot's inexperience with the malfunctioning system.

Design issues also were present. Among the causes of one incident was an incorrect altimeter setting. The reporter suggested that "perhaps another form of altimeter setting without a very sensitive knob would be helpful." Sun glare in the cockpit was a contributing factor to another incident. "Sun was shining on the glass cover of vertical speed window and had a bad glare. ...I had set in a plus instead of a negative value."

5.2.5 The National Plan for Aviation Human Factors Safety Issues

The National Plan for Aviation Human Factors identifies an issue concerning causal factors in accidents and incidents. The ability to predict and reduce human error relies on knowing why an error occurred. Existing accident and incident databases provide little information about why errors occur. The Plan cites a need to "improve the understanding of the root causes of human error, and to investigate procedural and design methods to reverse the adverse effects of error."

5.3 Cockpit Automation and the Pilot-Vehicle Interface

5.3.1 Definition

Automation has been defined as, "any use of a computer (or other machine) to perform tasks that might otherwise be performed by a human. It is the process by which essential functions are performed with partial, intermittent, or no intervention by an operator." (Hart and Sheridan 1984)

The definition can be narrowed to cockpit automation. Cockpit automation allows tasks or portions of tasks performed by the human crew that can be assigned, by the choice of the crew, to machinery. Usually these are control-type functions such as flight path guidance, power plant, or environmental control. The term, automatic, can refer to computational support and also to designs which allow procedures to be omitted by the crew. Another general use refers to cockpit warning and alerting systems — the machine monitoring the human.

The degree of automation can range from fully manual (human controlled) to fully automatic. In the manual extreme the design could lead to fatigue, high workload, and failures in detecting critical conditions. With a high degree of automation of both control and monitoring there are problems of boredom, complacency, and loss of competence (Wiener 1988).

5.3.2 The National Plan Objectives for Automation

The objectives for automation stated in the National Plan for Aviation Human Factors (1990) are:

- A. To identify the information required by flight crews to fly commercial air carriers and general aviation aircraft safely in the evolving NAS and to develop guidelines for designing and evaluating flight deck controls and displays with regard to their safety and efficiency of use by flight crews.
- B. To provide a standard set of assessment procedures and criteria based upon pilot performance and judgement that are useful for designing and evaluating instrument approach procedures.
- C. To develop and evaluate advanced flight deck systems technologies that provide flight crews with safe and effective ways and means to plan and replan flights, manage aircraft systems, and effectively respond to the external environment in dealing with contingencies.
- D. To provide human centered guidelines for automation technologies that ensure full situation awareness.
- E. To develop the technology necessary for the design of error-tolerant flight decks, including intelligent monitoring devices for flight deck procedures and concepts that provide assistance to the flight crew in investigating strategies that satisfy specific goals subject to system and aircraft constraints.
- F. To develop automation technology that supports the flight crew in time-critical situations.
- G. To develop intelligent flight crew aids that provide extensive fault monitoring and diagnosis capability.

These objectives offer a springboard for current and forthcoming research efforts.

5.3.3 Reasons to Automate

Cockpit automation is a topic of much debate. While researchers ponder which tasks should be automated or whether automation already has gone too far, a number of reasons for cockpit automation have emerged (Hart and Sheridan 1984, Stoll 1990, Wiener 1988, O'Hare and Roscoe 1990):

- Increased safety,
- Error reduction,
- Workload reduction,
- Performance improvement,
- Economic improvement,
- Efficient use of airspace, and
- Equipment reliability.

Wiener (1988) cites the potential of automation to augment human monitoring ability with warnings and alerting systems. O'Hare and Roscoe (1990) also mention alerting systems to warn the pilot of failures or hazardous states. A major goal of automation is to reduce the opportunity for human error. Automatic monitoring and warning systems help fulfill this goal.

Although automation and reduced workload are topics of debate, automation can free the pilot and crew from many routine operations. In addition, automation permits activities that humans do not have the capacity to perform (Wiener 1980, Hart and Sheridan 1984).

Automation has led to aircraft performance improvement. This has been accomplished through more precise handling of routine operations, more efficient power plant operations, and more precise flight maneuvers and navigation (Wiener 1980, 1988).

Hart and Sheridan (1984) have listed fuel efficiency, crew reduction, more reliable scheduling, and less reliance on ground support as economic benefits of automation. Wiener (1988) adds reduction of flight time and cost as additional benefits of automation.

With increasing traffic in the airspace, planes will need to be packed closer together through more precise lateral, vertical, and longitudinal (speed) navigation, less-rigid airway and approach and departure structures, and effective metering and spacing of aircraft arrivals. Wiener (1988) reports that flight deck as well as ground-based automation is required.

The reliability of automated systems is seen as both a positive factor for automated systems and a cause for concern. On the positive side, system safety is greatly increased. However, a concern has been raised that because of low failure rates, human controllers may be inadequately prepared to cope with automatic system failures (O'Hare and Roscoe 1990).

One additional reason for cockpit automation is economy of cockpit space. Multifunction displays can replace rows of electromechanical displays.

Implementing automation to free the pilot for scanning for other aircraft, especially in the terminal area is an important reason to automate aircraft operations. It is essential for pilots to spend less time with their "heads in the cockpit" and more time scanning (Wiener 1988). Accident statistics support this statement. A report of safety statistics (Caesar 1987) shows that 75 percent of all accidents occur within the vicinity of the airport.

5.3.4 Automation Concerns

Automation concerns range from taking the pilot "out of the loop" to implementing automation simply because it can be done. Wiener (1988) voices the controversial nature of cockpit automation.

Cockpit automation is a subject that evokes considerable controversy among users, manufacturers, and regulatory agencies. ...Automation is regarded at one extreme as a servant, relieving the human operator of the tedium of momentary control, freeing him or her for higher cognitive functions. At the other extreme it is viewed as reducing the status of the human to a "button pusher," and stripping the job of its meaning and satisfaction. Many see cockpit automation as a great boon to safety, removing human error at its source and replacing fallible humans with virtually unerring machines. The critics view automation as a threat to safety, replacing intelligent humans with devices that are both dumb and dutiful, a dangerous combination. There appears to be ample evidence to support both positions; however, as usual, the truth undoubtedly lies somewhere between the extremes.

Human factors literature cites automation concerns as well as some possible solutions (Choreley 1984, Hart and Sheridan 1984, Henderson 1992, Hughes 1989, O'Hare and Roscoe 1990, Phillips 1992, Stoll 1990, Wiener 1988, Poduval 1987).

5.3.4.1 Pilot Concerns

Concerns about automation mentioned by pilots include:

- Maintaining sufficient alertness to perform adequately activities which the automated systems cannot undertake;

- Maintaining aviation skills;
- Reduction in system understanding;
- Reduction in job satisfaction;
- Crew complacency, lack of vigilance, and boredom;
- Making a transition between automated and nonautomated aircraft;
- Placing too much trust in automation — lack of dependence on airmanship;
- Overreliance on automation — inadequate preparation to deal with automatic system failures;
- Loss of sense of reality — false perception of reality as that of the keyboard and display device;
- Reluctance to take over from an automated system, despite evidence of malfunctions;
- Lack of challenge brought about by automation assuming more and more crew tasks; and
- Being removed from the "control loop".

5.3.4.2 Design Concerns

Concerns about design pertain to the actual devices or systems and how they operate. These concerns include:

- CRT-displayed legends that vary according to the current mode of operation,
- Multi-function switches that reduce the number of switches in the cockpit, but introduce complexity and the need for a greater amount of training,
- Devices or system designs that limit the pilot's ability to respond when the unexpected occurs,
- Flight management systems with cumbersome interaction, and where improper programming can introduce error,
- High false alarm rates that lead to failure to respond to genuine alarms,
- Inadequately designed keyboards which result in input errors,

- Automation that reduces the number of small errors but invites new forms of operational errors,
- Premature introduction of equipment,
- Fault intolerant systems,
- Technology that allows silent failures,
- Failures induced by automation, and
- Systems that are too complex and allow pilots to be "surprised" by automatic features.

5.3.4.3 Information Management Concerns

Information management becomes especially critical in glass cockpits where a small number of display devices replace numerous dials and gauges. These concerns were expressed in the literature:

- The amount of information displayed is simpler, but may be less accessible. The pilot must learn how to access information.
- Designers rather than pilots may determine what information is essential.
- Too much programming and "heads down" time takes place below 10,000 feet and in the terminal area.
- Lack of situational awareness in identifying and correcting the problem can exist when an automated system fails.

5.3.4.4 Training Concerns

Concerns were raised about inadequate and insufficient training in a number of areas. These include understanding automated systems, knowing when to shut down an automatic system and revert to manual flying skills, making transitions between automated and nonautomated aircraft, and understanding the designer's intent for the automated system.

5.3.4.5 Workload Concerns

Concerns about crew workload were raised. Many pilots felt that automation actually increased their workload. The nature of pilot workload has changed with automated systems. Workload from manual tasks has declined while monitoring and mental workload have increased. Workload associated with reprogramming flight management systems in response to air traffic controls also was mentioned.

5.3.4.6 Possible Solutions and Improvements

A number of possible solutions and improvements were offered by the researchers. Selective application of automation and allowing the pilot to choose the automatic or manual mode were suggested. It was recommended that automation be designed to assist and not supplant the pilot. Such automation could appear in innovations such as electronic checklists and digital data links between the ATC system and aircraft (Henderson 1992). It is interesting to note that most proposed solutions focused upon keeping the pilot "in the loop."

Poduval (1987) compared the glass cockpit pilot to an "over-loaded flight deck computer." He suggested that systems provide the level of automation that will at all times give the crew correct and relevant information regarding the status of the aircraft, automation that will not create a feeling of unfamiliarity and breed insecurity, and automation that will keep the pilot in the control loop.

5.3.5 Guidelines for Cockpit Automation

Wiener and Curry (1982) proposed a set of guidelines for developing and using automation. Guidelines include control tasks and monitoring tasks.

Control Tasks

- Design systems that can be understood easily by the pilot. This will facilitate the detection of improper operation and the diagnosis of malfunctions.
- Design the automatic system to perform the task the way the user wants it done.
- Design automation to prevent peak levels of task demand from becoming excessive.
- Train the pilot to use automation as an additional resource when task demands are high.
- Design systems that can accommodate different pilot styles when feasible.
- Ensure that overall system performance will be insensitive to different options, or styles of operation.
- Provide a means for checking the set-up and information input to automatic systems.
- Provide sufficient training for pilots working with automated equipment, to ensure proper operation and set-up, and ensure knowledge of correct operation and malfunction procedures.

Monitoring Tasks

- Train, motivate, and evaluate pilots to monitor automated systems.
- Provide meaningful duties to maintain pilot involvement and resistance to distraction if automation reduces task demands to low levels.
- Keep false alarm rates within acceptable limits.
- Clearly indicate which condition is responsible for an alarm display. This is especially critical for multimode systems.
- Provide alarm information in the proper format so that a validity check can be made quickly and accurately and not become a source of distraction.
- Provide the pilot with information and controls to diagnose the automatic system and warning system operation.
- Format the alarm to indicate the degree of emergency.
- Devise training techniques and possibly training hardware to ensure that flight crews are exposed to all forms of alerts and to many of the possible combinations of alerts, and that they understand how to deal with them.

The ASRS, sponsored by NASA, makes available reports of aviation incidents submitted anonymously by pilots and crew members. A request for reports referencing advanced cockpit flight guidance systems involving two-engine, advanced cockpit, widebody aircraft yielded 55 reports. It is interesting to note that a large number of incident narratives mentioned input mistakes and lack of training as an incident cause.

McDaniel (1988) developed a set of rules for automating fighter cockpits. Although developed for military aircraft, they are relevant to commercial aircraft.

1. The pilot shall be provided the capability to override, disable, or disconnect automated functions.
2. The pilot shall be provided the capability to determine the status of any function, state, or action either by continuous display to the pilot or upon command of the pilot.
3. The decision to fire weapons cannot be totally automated. As a minimum, the pilot must give informed consent to enable an otherwise automated process.

4. Every pilot input to the system must be acknowledged with a response observable by the pilot.
5. In the event of failure of an automated function, it should be fail-safe (where subsystem failure does not cause a hazard to the system) and fail-soft (where the failure of one subsystem or function does not cause unnecessary degradation of another subsystem or function).
6. Before an automatic function can take over from an incapacitated pilot, the pilot must be queried and fail to respond.
7. If an aircraft has more than one automated function, the automation design must be consistent with respect to operation, feedback, and override characteristics.
8. When a pilot disables or selects manual backup, this status mode must be displayed to the pilot.
9. Automated systems will present only relevant information or data to the pilot. The information presented to the pilot should be relevant to the current mission segment, or a future segment (if intended as a preview).
10. Automated systems will not present erroneous information to the pilot. If the accuracy of the information is uncertain, it must be so identified or coded.
11. Critical functions which are automated must have a manual backup, and/or redundant automation, especially if the reaction time of the pilot is too long to be effective in all situations.
12. If a manual override exists, it must be continuously available for selection by the pilot. If the automated function is critical, the override shall be activated with a single control action.
13. If a system has one or more levels of redundancy, the number of levels available (i.e. unfailed) should be displayed to the pilot.
14. If a delay is involved, or if a time cue is relevant, the time remaining will be displayed to the pilot.
15. During the transition period, after overriding or interrupting an automated function but before the pilot's initial control input, the function will maintain a safe or neutral state until the pilot has taken control.

16. During the transition period, after a failure of an automated function but before the pilot's initial control input, the function will cue the pilot to take control and maintain a safe or neutral state until the pilot has taken control.

5.3.6 The Role of the Pilot and Crew in an Automated Cockpit

With the introduction of cockpit automation, the nature of the pilot's role is changing. Automated systems have assumed some of the pilot's responsibilities while system operation and monitoring responsibilities have been added to the pilot's job.

One fear expressed by the aviation community is that the pilot will be automated "out of the loop" and will be ill-prepared to respond to system failures or emergencies. To help the pilot maintain situational awareness it has been suggested that automated systems be designed for a "human-centered" cockpit. In the human-centered cockpit, automated systems provide maximum assistance while allowing the pilot to remain in control. The system works in concert with the strengths of the human and the machine.

It should be stated, however, that pilots of modern transport aircraft are not "in the loop" in the traditional sense. The degree of sophistication and complexity of newer transport aircraft require some form of computer assistance at all times to fly the aircraft. Factors such as economics and safety ensure that utilization of computer-automated flight will continue. Therefore, issues relating to the "pilot in the loop" also will remain with us.

The design of technology-based systems focuses upon automation capabilities. The human operator of the system may not be a primary consideration of the design. The National Plan for Aviation Human Factors (Volume 1 1991) cites the hazards of designing technology-based systems in which the pilot's chief role is that of system monitor. They mention that a human error-reduction approach to automation has resulted in highly reliable systems with superior performance capabilities, however, new classes of errors have evolved when the human operator assumes the role of system monitor. These new errors can be worse than the ones successfully eliminated.

Operational problems can arise when an automated system has been designed to be technology-centered. The operator may be left with an arbitrary collection of tasks and expected to monitor the system and take over should anything go wrong. With technology-centered systems, a problem that arises is that the operator may possess less experience in the skills necessary to operate the system in manual mode. When the operator intervenes manually, there often is more to take care of because automation may have increased the system's capabilities. Also, the operator may be assuming control when the system has malfunctioned and workload is at its peak. Lapses of attention to monitoring the system may leave the operator unaware of the problem. With technology-centered systems, the operator is expected to stay alert in boring situations, and if anything goes wrong, to perform more complicated operations with less experience.

Hart and Sheridan (1984) describe possible ways for human/machine responsibilities to be delegated.

- The system suggests decision alternatives that the human may accept or ignore.
- The system offers decision alternatives. The human must select the alternative and implement it.
- The system offers decision alternatives and then implements the one selected by the human.
- The system makes decisions but informs the operator in time for human intervention before implementation.
- The system makes and implements decisions and informs the operator after the fact either routinely or only on demand.

The two main roles of a pilot are controlling the aircraft and monitoring the status of the aircraft. Two terms frequently associated with the pilot's control of an aircraft are "in the loop" or "out of the loop." A loop is a continuous process of action, feedback, comparison, and further action. A system may be comprised of a hierarchy of loops with a planning and directing loop at the top of the hierarchy. The direct manipulation of an aircraft's control elements would be the lowest level of the hierarchy. When a pilot is involved actively in the loop process he is said to be "in the loop." In automated systems it has become routine to remove the pilot from the lowest loop during most of the flight. Studies have found that an active controller, or one who is "in the loop," is able to detect changes and errors in the system significantly faster than an inactive controller or monitor. However, it was found that gradual errors were better detected by those in a monitoring position. There is no single or simple answer to the distribution of control functions between crew members and automatic devices (O'Hare and Roscoe 1990).

Although the choice to use automated systems is often that of the pilot, some carriers require the constant use of automation in the belief that computers are safer than pilots. Here the role of the pilot is shifted toward that of a monitor. These organizations choose to remedy manual skill deterioration through recurrent simulator training.

Edwards (1990) examined the controlling and monitoring role of the pilot in an automated aircraft. Alternatives include:

- The automated system controls the aircraft and the pilot monitors the system,
- The pilot controls the aircraft and the system monitors performance,
- The pilot and the automated system each have systems to control and each monitors the other's performance.

In the future, a "pilot's choice" system would permit each pilot to perform as much of the flying as can be handled. The computer would monitor and assess what was being done, correct what was done poorly, and take over functions that were not being done according to standards. With this system, pilot skills would be maintained and given constant reinforcement from continuous feedback.

The pilot-crew process also is changed in an automated cockpit. There is a shift in power boundaries — the actual control and command of the aircraft belongs to whomever is controlling the FMS computer. In addition to a shift in power, communication requirements have changed. Large amounts of information must be shared, coordinated, and processed into the crew routine. In response to the demands of the automated cockpit, SOPs must reflect a more demanding, highly coordinated behavior to manage the more elaborate task activity (Maher 1992).

Wiener (1988) presents the concept of flight management by exception. In this role the crew determines how the aircraft will be flown, within the bounds of regulations, ATC, and flight safety. With this concept, the crew is allowed maximum flexibility in operating devices. The system provides warnings and alerts to inform the crew when an unacceptable condition is about to ensue.

Within the concept of management by exception is the "electronic cocoon," a multidimensional shell around the aircraft and crew. As long as the flight stays within the cocoon, the system allows the crew to fly as they see fit. If the cocoon is penetrated or is forecast to be, an exception message is issued. While favoring this idea, Treacy (1992) indicates that more work is needed, especially with the autopilot. Delays within a system or in identifying and reporting a failure can cause problems.

The role of the crew in management by exception requires clear communication of intent not only among crew members but also with the automated system. Goal sharing (intent driven systems) requires the crew to make its intentions known and then allows the computer to check crew inputs and system outputs to see if they are logically consistent with the overall plan. If not, an exception report is issued.

In summary, automation is changing the role of the pilot and crew. With automation, the crew is faced with more monitoring responsibilities. One fear is that with fewer control responsibilities, the crew will be "out of the loop" and less prepared to deal with failures and emergencies. The National Plan for Aviation Human Factors advocates the development of human-centered automation concepts and tools rather than technology-centered systems in which the crew's chief role is that of system monitor. It was found that operators in an active controlling role detect errors in the system faster than those in a monitoring role. Automation has changed the psychosocial roles of the pilot and crew. Power shifts to whomever is in control of the FMS computer. With automated systems, there is a greater need for communication and coordination. The electronic cocoon has been proposed as a method of implementing human-centered automation. The electronic cocoon allows the crew to determine the control of the

aircraft within the bounds of ATC and flight safety. If the cocoon is penetrated or is predicted to be, an exception message or warning is issued.

5.3.7 Error Management in the Automated Cockpit

Error reduction is one of the goals of automated systems. While cockpit automation has reduced many human errors, it has opened the door to others. Data input, especially into the FMS, appears to be a source of problems. When testing an McDonnell-Douglas MD-11, Charles (1992) commented on the computer/pilot interface. He found that data keying errors returned a FORMAT ERROR message but gave no feedback to assist the user. A greater danger was identified by Wiener (1988). Programming errors such as miskeyed waypoints introduced early in the flight may not be realized until later in the flight.

Training is mentioned as a key to understanding and operating automated systems. However, it also is cited as a dumping ground for problems created by cockpit design and management. Wiener (1988) suggests a number of approaches to error prevention:

- Design systems to be less cordial to error at the human interface rather than depending on training and correct operation.
- Design systems to be less vulnerable once an error is made.
- Provide error-checking mechanisms.

5.3.8 Automation Issues and Questions

A number of automation issues and questions pertinent to the design, evaluation and implementation of automated systems are raised in the human factors literature (Erikson 1991, O'Hare and Roscoe 1990, The National Plan for Aviation Human Factors 1990, Wiener and Curry 1982, Treacy 1992, Wiener 1988, McDaniel 1988, Proceedings: Cockpit Electronic Display Workshop 1992).

5.3.8.1 Pilot Skills and Automation: Issues and Questions

- If the automated system will lead to possible deterioration of manual skills, has some means of compensating for this loss been incorporated into the system?
- How rapidly will manual flying skills deteriorate by using the automatic system?
- How will the pilot monitor the state of the system?
- What quality control techniques have been incorporated to ensure maintenance of manual flying skills?

- How are pilot skills affected by consistent use of automation and managed information displays?
- How quickly can the pilot make the transfer from automatic to manual flight?
- How will the pilot know when to override the automatic system and fly the aircraft manually?

5.3.8.2 Pilot Psychosocial Aspects of Automation: Issues and Questions

- Will the system lead to pilot complacency and loss of situational awareness resulting from overreliance on automation?
- How can overreliance on automated systems be prevented?
- Will loss of direct control adversely affect job satisfaction?
- Will the pilot become detached from the outside world?
- Will crews be less able to respond to an emergency with the automated system?
- What pilot selection criteria will need to be modified to identify individuals best able to handle automated systems?
- Will pilots prefer to remain on older, less automated aircraft rather than upgrade to automatic systems?
- If there are negative psychosocial consequences of automation, what precautions or remedies will be effective without changing the use of automation?

The National Plan for Aviation Human Factors identifies aircrew complacency as an issue. There is concern that increased flight deck automation may have deleterious effects on aircrew attention and performance. The Plan expresses a need to conduct research to determine the relationship of flight deck automation to crew complacency, performance, and flight safety and to correct for any undesirable effects.

5.3.8.3 Pilot Training and Automation: Issues and Questions

- How much knowledge must the pilot have of the automated system?
- What training procedures will be required to cope with skill decay?
- What training procedures will be required to facilitate the switch between aircraft with different degrees and kinds of automation?

- Must the pilot be trained in computer technology and programming to use the automated system effectively?
- Will periodic practice prevent skill deterioration? If so what frequency of practice is required?
- Can simulator experience provide an alternative to actual time on the system for learning the automated system?
- How do training programs need to be altered to accommodate the automatic system?
- How can pilots be trained to recognize when automated features should be downgraded and to what level?

5.3.8.4 Workload and Automation: Issues and Questions

- Does the system achieve a balance of pilot workload among visual, auditory, and manual task demands?
- Does the automated system decrease workload or add to it?
- Will the automated system relieve workload during high workload phases of flight?
- Will the automated system require substantial heads down time during high workload portions of flight?

5.3.8.5 Design and Automation: Issues and Questions

- Does the computer interface minimize head down time associated with data entry and programming?
- If there are standards established for the system, does the system adhere to them?
- Is there a checking mechanism in place to ensure that only correct information is entered into the system?
- Does the system include a safeguard to prevent inadvertent activation or deactivation of the system?
- Does the system notify the pilot of automatic system corrections?
- Will the automatic system make configuration changes and then inform the pilot or will it make the changes only after pilot acknowledgement? Does the system indicate why the changes are being made?

- How does the system make the operator aware of changes?
- What types of tasks should be automated? What tasks should not be automated?
- What are the pilot's information needs at different phases of flight and different conditions of flight?
- Do the benefits of the automated system outweigh the cost of the system?
- Are the interfaces to the cockpit automated systems consistent?

5.3.8.6 Alarms and Failures and Automation: Issues and Questions

- How does the automated system handle computer failure?
- How does the system handle data conflicts?
- How are unforeseen circumstances dealt with?
- Are alarm validity checks built into the system?
- Does the computer determine the priority of alarms? If so, how is this hierarchy determined?
- What is the impact of different levels of equipment reliability on the operator's ability to detect, diagnose, and treat malfunctions in manual and automatic tasks?
- How easy is it to detect and diagnose malfunctions of the automatic system?
- Is the false alarm rate of the automatic system unacceptably high?
- Under what conditions should the validity of an alarm be checked?
- Will pilots be able to detect errors in electronic databases?
- Is the status of the automated system effectively displayed to the pilot?

5.4 Design Issues and the Pilot-Vehicle Interface

5.4.1 Cockpit Design Philosophies

There is a move toward human-centered automation and involving pilots and human factors specialists in the design phase of automated systems. Many manufacturers retain a human factors group and qualified pilots as part of automated systems design teams. Since cockpit systems

have become so complex, it is impossible for one designer to be responsible for an entire system. The team approach is favored.

The role of the pilot in the design process is stressed by many manufacturers. Honeywell maintains a staff of air-transport-qualified pilots to work with airlines and aircraft manufacturer committees, to stay in touch with end-users. Pilots at Honeywell and at Douglas Aircraft had considerable influence on the development of features for the McDonnell-Douglas MD-11 cockpit. One of the challenges undertaken by Collins was to design an automated cockpit in which the pilot could intervene when necessary then resume automatic operations (Aviation Week and Space Technology, March 23, 1992).

The McDonnell-Douglas MD-11 design philosophy stresses the importance of the pilot. The design philosophy behind the automated systems in the McDonnell-Douglas MD-11 was to give the pilot maximum assistance while allowing him final authority. The design provides the pilot an electronic flight engineer to manage systems, "and another helper — something like a wise old check airman — to keep the pilot out of trouble" (Charles 1992).

Oldale (1990) describes the Douglas flight deck design philosophy:

- All functions from preflight to shutdown at the termination of flight require little input from the crew.
- In most cases, system reconfiguration as a result of a malfunction is automated.
- Manual input is required for irreversible actions such as engine shutdown, fuel dump, fire agent discharge, or integrated drive generator disconnect.
- During normal operations, when the cockpit is configured for flight, all annunciators on the overhead panel are extinguished.
- Primary system annunciators are shown in text on the alert area of the engine-and-alert display. This eliminates the need to scan overhead.
- Major system controls are in a central position on the overhead panel and are accessible from both flightcrew positions.
- There is design consistency within and between control panels.
- Panels most frequently accessed are in the lower forward area. Panels less frequently accessed are in the upper aft area.
- Pictorial schematics are used for control panels.
- Each Aircraft System Controller (ASC) has two automatic channels and a manual mode.

- If the operating automatic channel fails or is shut off by its protection devices, the ASC automatically selects the alternate automatic channel. If both automatic channels fail, the controller reverts to manual operation and the aircraft is reconfigured to a safe condition. The crew would employ manual operations for that system only.
- All rectangular lights are annunciators.
- All square lights are combined switches and annunciators called switch/lights. Red switch/lights require immediate action, amber indicate a fault or switch out of position requiring awareness or crew interaction. Switches in normal operating conditions will illuminate blue when in use.
- An overhead switchlight with black lettering on amber or red indicates a system failure and that crew interaction is required.
- Blue or amber lettering on a black background indicates a switch out of normal position and that crew action is required only if the system is in manual operation.

Boeing also stressed the importance of including human factors personnel and pilots in the design process. For development of the Boeing 777 cockpit a group of human factors specialists highly qualified in cognitive psychology and other disciplines worked with engineering personnel at the grassroots level. Also, the company had an active working group of airline pilots to evaluate the Boeing 777 cockpit (Phillips 1992).

Design of the Boeing 777 has been monitored by hundreds of pilots and other flight deck specialists representing airlines, industry groups, and regulatory bodies worldwide. The aircraft is automated to the extent necessary to get the information onto the aircraft. But the crew is still involved in reviewing the message, deciding to accept it, and having the autopilot act on the information. Automation is employed in such a way that the pilot remains in the decision loop and the pilot's awareness of the situation is preserved (O'Lone 1992).

Maher (1992) offers general design and operational philosophy recommendations:

- Present information in language that relates to the way pilots think when they fly.
- Design the pilot and crew into the loop during low workload events. Provide antidotes to boredom during long legs of flights. Assist the crew during periods of high workload.
- Airplanes can operate using basic raw data, using the flight director to control the plane, or using full autoflight. Design equipment and training to enable proficiency at each level, and simple transitions between levels.

- Apply error resistance and error checking Artificial Intelligence (AI) programs to all programming functions.
- Do not build hard electronic protective cocoons. They have caused crashes and can deprive pilots of tactile feedback in events such as low level windshear recoveries.
- Use technology to build, maintain, and reinforce teamwork.
- If the aviation system is unwilling to fund electronic glidescope guidance on all runways served by air carriers, build aircraft technology that will generate internal precision glidescopes.

A number of problems are associated with developing a human-centered philosophy of aircraft automation (Phillips 1992):

- Changes in ATC instructions require reprogramming flight paths. The task requires considerable attention and usually must be performed when workload is already high.
- Some new devices increase workload when it is at its highest (during approaches, climbs, and descents), and decrease workload when it is already lowest (during cruise flight and at high altitude).
- Aircraft such as the Boeing 747-400 and Airbus A320 incorporate attempts to simplify MCDU operation by making available more comprehensive navigation databases and adding software to make reprogramming simpler. However some pilots and designers have advocated replacement of MCDU keyboards with other data entry devices or by incorporating software for a more user-friendly interface.
- Automation introduces the possibility of making data entry errors.
- Multimode devices can lead to misunderstanding of autopilot modes or undetected mode changes.
- The ability of the autopilot to operate transparently until its limits are exceeded can be hazardous.
- Crew coordination can be adversely affected by highly automated systems. The pilot flying the aircraft may not be aware of changes to an automated system that were entered by the other pilot. The result is a loss of situational awareness.
- Present automation makes it easy to operate the aircraft under normal conditions but more difficult to operate under exceptional conditions.

- The role of pilot for human-centered automation has the system provide less assistance during nominal conditions and more under difficult circumstances. This keeps the pilot "in the loop." The pilot calls on automation to assist in problem diagnosis, evaluation of alternative solutions, execution of alternative plans, providing and calculating data, watching for the unexpected, and tracking resources and rate expenditure.

Pilots must have an active role in controlling or managing the systems to which they delegate control of the aircraft. To be involved, the pilot must be informed. The pilot must be able to monitor the automated systems and the systems must be predictable. Air crews must be able to evaluate system performance and quickly detect and recognize deviations from normal operation. Automated systems must be able to monitor the human. Because pilots are fallible as well, automated systems need the capability of monitoring crew performance. Each element of the system must know the other's intentions (Phillips 1992).

5.4.2 Cockpit Layout and Devices

The design of control layouts in World War II aircraft was particularly haphazard. This led to many accidents and incidents caused by misidentification or misoperation of a control. These mishaps spurred research on the placement and design of cockpit instruments.

O'Hare and Roscoe (1990) developed general guidelines for cockpit control placement:

- Controls and displays should be accessible and legible.
- The area that can comfortably be scanned by eye movements alone is about ± 30 degrees in the line of sight. One violation of locating controls in this area is the fuel on/off indicator. In many light aircraft it is placed by the pilot's left ankle or entirely out of view. Nearly 20 percent of general aviation engine failure accidents are caused by fuel starvation.
- The layout of instruments should be based on each instrument's importance, its relative frequency of use, its similarity to other instruments, and any requirements governing sequence of use.
- Controls and displays that are located less centrally but must be used quickly in an emergency may benefit by shape and color coding.
- Population stereotypes must be known for the pilots who will be operating the equipment. Instruments that fail to conform to stereotypical relationships will be more difficult to operate and will give rise to operating errors, especially under conditions of fatigue or stress.
- Moving Horizon displays should be designed so that pilots cannot mistake the horizon bar for the wings of the airplane and reverse the direction of their aileron control inputs.

- The part of the display that moves in response to a control input, should move in the same direction as the control input.
- Predictive displays should be used to show the pilot the future effects of present control inputs.
- Involve pilots in early design stages.
- A digital display of own aircraft track, speed, and map scale should be included in displays.
- Significant terrain features should be displayed with labeled heights.
- A chevron symbol is preferred for own aircraft.
- Some information about other aircraft in the vicinity, in the form of digital data tags, should be available on demand.

Green et al. (1991) mention that the pilot should be able to view all important displays and be able to maintain an adequate view of the outside world without the necessity for more than minimal head movement. Additional considerations for flight deck control design and placement include:

- Frequency of use,
- Sequence of use,
- Importance of control,
- Simultaneous use,
- Visual/tactile dissimilarity,
- Symbolism in control design,
- Control/display compatibility,
- Prevention of inadvertent operation, and
- Standardization.

When asked about the nature of displays on digital aircraft now and in the future, Treacy (1992) indicated that the tendency is to reduce the number of displays but increase their complexity.

Treacy predicted that the trend would not be to add more displays but to have a more centralized system with more options. Thus the complexity for the crew is greater.

One cockpit device that can aid the pilot by allowing communications with ground sources is the data link. This facility allows computers in aircraft to communicate with computers on the ground. Weather data, routine ATC instructions and clearances, and collision avoidance information can be obtained through the data link (Williges, Williges, and Fainter 1988). Advantages of the data link are fewer missed or misunderstood communications and pilot workload reduction during critical phases of flight (Sexton 1988).

A VHF data link is used by Air Canada Boeing 767 crews to receive oceanic clearance for crossing the North Atlantic. The data link is especially helpful when approaching a destination in deteriorating weather. It is possible to call up and print out the latest weather observations without making a radio call. Because Air Canada's data link is tied into the company's flight operations computer, almost every type of message can be called up or received.

One data link problem is standardization: the keyboard on Collins data link is substantially different from that on the Honeywell FMS, so pilots have to remember two keystroke patterns (Hughes 1992).

5.4.3 Information Presentation, Organization, and Access

Pilots in a digital cockpit exist in an information-rich environment. The challenge for designers is to organize and present this information in a meaningful and accessible manner. During abnormal conditions, pilots do not have the time to select critical information from unimportant information. The task for the system designer is to provide the necessary information in a timely and comprehensible manner while maintaining pilot workload within an acceptable range (Allen 1989).

Williges and Williges (1984) have compiled an extensive review of dialogue design literature. This document was not intended to be a handbook, rather it was an attempt to bring together the variety of guidelines for dialogue design in the form of user considerations. Because relevant user considerations can vary from application to application, some of the considerations may be conflicting. The designer must decide which are appropriate for the specific display application. The review includes an extensive reference list. Findings relevant to cockpit display for the PVI include:

Information Coding

Information coding should be used to discriminate among different classes of items presented simultaneously on the screen.

- Use meaningful codes that are clear and consistent with the user's expectations.

- Use highlighting for critical information.
- Information should not be overused — the value of coding will diminish or become distracting.
- If type-of-information coding reduces legibility, is not distinct, or increases transmission time, it should not be used.
- Colors are best used to highlight, locate, emphasize, separate (group), and for search tasks.
- Information should not be coded solely by color if information can be accessed from a monochrome terminal or if hard copy versions will be made.
- Color should be used conservatively to avoid clutter.
- No more than 11 color codes should be used.
- Consider color meanings, for example, red to signify danger.
- Color codes should be displayed at the bottom of the screen.

Shape Codes

- Use shape codes in search and identification tasks.
- Use no more than of 15 different shape codes.

Blinking Codes

- Use blinking codes for alarms.
- Use blinking codes for coding in target detection tasks.
- Allow the user to turn off blinking.
- Blinking should turn off when user has responded.
- Blink rate should enable user to scan or read the item.
- To attract attention a 2 to 7 Hz blink rate should be used.

Brightness Codes

- Highlight item to be operated upon.
- On crowded displays, level of brightness can distinguish the labels.
- Options selected by the user should be highlighted.
- No more than 10 percent of the display should be highlighted at one time.
- No more than three levels of brightness should be used.
- Use maximum contrast between highlighted items and those that are not.

Alphanumeric Codes

- Use alphanumeric codes when absolute identification is important.
- Be aware that problems can arise with confusion among similar symbols, space for symbols, learning meaning of symbols.
- Avoid confusing pairs such as I-1 or O-0.

Information Density

- The number of items displayed simultaneously should be minimized.
- Only information essential to the user's current needs should be displayed.
- Interim data should be removed from the screen once they are no longer needed.
- All data related to the user's current task should be displayed simultaneously, if possible.

Labeling

- Label variables or column heads.
- Identify units.
- Labels should have distinct and meaningful wording to distinguish them from warnings.
- Items continued on the next page should be numbered relative to the first item on the initial page.

- Every display frame should have a unique identifier to provide a reference.

Format

- Use standards appropriate for the intended users.
- Identical data should be presented to the user in a standard and consistent manner.
- The same data format should be used for related input and output.
- Formats for data entry in form filling dialogues should match the source document format.
- Essential data, text, or formats should be under computer control. Never assume voluntary compliance by the user.
- When meaningless or arbitrary codes must be remembered or entered by the user, they should be no longer than four alphabetic or five numeric characters.
- Data entries should not exceed eight to ten characters.
- When items longer than seven characters must be entered, they should be partitioned into smaller symbol groups.

Prompts

- A special character can be used to denote an input prompt.
- Input prompts should be clear and understandable.
- Highlighting methods should be used to make prompts stand out.
- The cursor form should be distinctly different from any other displayed items.
- In graphics applications the cursor should be distinct from graphical shapes displayed.
- Input prompts should be placed in a consistent screen location.

Tabular Data

- Data to be scanned and compared by the user should be presented in graphic or tabular form.
- Items in a list should each start on a new line.

- Items in a list should be arranged in some recognizable and useful order.
- For items in a list that will not be used for input selection, "bullets" may be used to enumerate the items.
- Lists should be left justified and aligned vertically.
- Subclasses can be indented.
- Tabular displays should be broken into blocks.
- When a list extends beyond the amount shown on the display page, a short message should indicate that the list is not complete.

Graphics

- Label the axes of graphs.
- Labels for graphs should describe what is being displayed.
- The axes of graphs should be subdivided with appropriate divisions (1, 2, 5, 10).
- The number of graduated marks between numbered scale points should be no greater than nine.
- Scales should be numbered starting at zero.
- Increases in magnitude on scales should be clockwise, left to right, or bottom to top.
- Maximum contrast between scale markings and the value displayed should be maintained.
- If a user shrinks a graphic display, labels must not be contracted to the point where they cannot be read.
- Symbols should be designed with consideration of graphic conventions to which the user may be accustomed.
- Unnecessary ornamentation, unwanted graphic patterns and illusions, and flaws in alignment should be avoided.

Textual Data

- Use active voice whenever possible.

- If a sentence describes a sequence of events, the word order should correspond to the temporal sequence of events.
- Use short, simple sentences.
- Statements should be made in the affirmative.
- Text should be displayed in a mixture of upper and lower case.
- Text should be left justified.
- Paragraphs should be separated by at least one blank line.

Numeric Data

- Numeric codes should be restricted to six or fewer digits.
- Long numeric fields should be punctuated with spaces, commas, hyphens, slashes, or some other appropriate punctuation scheme.
- Lists of numbers without decimals should be right justified.
- Lists containing decimals should use decimal alignment.
- Leading zeros should not be required in numerical data except when needed for clarity.

Screen Layout

- The organization of display fields should be standardized. Functional areas should be in the same location on all screens.
- Data should be presented using spacing, grouping, and columns to produce an orderly display.
- Data should be arranged in logical groups such as sequence, function, or frequency of use.
- Data should be arranged for ease of observation of similarities, differences, trends, and relationships.
- Keyboard echoing and messages from the computer should be distinguishable from one another.
- Related data should be clearly grouped.

- In computer-initiated dialogues, each display page should have a title that indicates the purpose of the page.
- Instructions should stand out.

Stokes and Wickens (1988) cite some advantages and cautions for use of color and color coding in displays:

Advantages

- Color facilitates location and processing of information.
- Color reduces confusion resulting from visual clutter and high workload.
- Color can be used to group data into larger categories of information more efficiently processed in short-term memory.
- Color benefits maps by providing broad categorization powers.
- Color can be used to separate and contrast different elements in a display that cannot be separated in space.
- Color aids selective attention by highlighting particular elements of a display.
- Color serves as an attention cue.
- Color is less distracting than devices such as flashing lights or auditory signals, and, for noncritical information, may be superior.
- Environmental colors such as blue/sky, brown/ground, can be used.
- Traditional colors such as red, amber, green for danger, caution, advisory, can be used.

Cautions

- Using a full range of colors may increase visual clutter.
- The optimum number of colors will vary with type of display and presence or absence of other coding dimensions.
- Pilots favor full-color pictorial formats for HDDs, but monochrome for HUDs since color obscures the external view.

Stokes and Wickens also discuss decluttering and configuration. Decluttering is an automation option that allows the pilot to temporarily remove items of information that are not relevant to the task at hand. They found that allowing the pilot to choose what and how much information should be displayed on a panel may decrease visual workload, but it may impose unwanted workload related to memory and response. The pilot must remember what is not being displayed and how to retrieve it if needed. The continuous visual presence of an instrument or dial in a non-automated cockpit is a reminder that it needs to be inspected. This reminder is eliminated by the configurable display concept.

Another problem is getting "cognitively lost" in a computerized menu system while trying to maintain situational awareness. Such problems have led to the development of an intelligent on-board computer to decide how displays should be configured and at what time specific information should be displayed.

Arkusinski (1986) reports problems that can make a display unacceptable:

- Related information displayed on different pages,
- Inappropriate formats (leading zeroes or blanks, upper or lower case),
- Inappropriate display of trivial error or warning messages,
- Omission of important error messages,
- Unnatural flow between display pages,
- Poor page layout or cryptic information, and
- Keystrokes that are repetitive, too numerous, or use an unnatural sequence.

Green et al. (1991) indicate that the type of display depends on the kind of data required. Purely quantitative data is best represented by a digital presentation. If qualitative and rate information are important, some form of analog display is preferable. If reference to the absolute endpoint of a scale is important, then moving tape displays should be avoided. If the display is to be used only to enable the pilot to know when some parameter reaches an undesirable state, then a simple warning is preferable to either analog or digital displays.

Williges, Williges, and Elkerton (1987) report principles to consider in human-computer interfaces:

- Compatibility: Minimize the amount of information recoding that will be necessary.
- Consistency: Minimize the difference in dialogue both within and across various human-computer interfaces.

- **Memory:** Minimize the amount of information that the user must maintain in short-term memory.
- **Structure:** Assist the user in developing a conceptual representation of the structure of the system so that they can navigate through the interface.
- **Feedback:** Provide the user with feedback and error correction capabilities.
- **Workload:** Keep the user mental workload within acceptable limits.
- **Individualization:** Accommodate individual differences among users through automatic adaptation or user tailoring of the interface.

Green et al. (1991) describe guidelines and problems for system warnings:

Guidelines

- Warnings should be attention-getting but not startling. A problem for designers is deciding what is important enough to warrant attracting the pilot's attention.
- Warnings should inform or report. It is sometimes suggested that guidance also be given.
- *Important failure annunciation should be an audio warning.*
- An ideal organization for aircraft warning systems is for a single audio warning to alert the pilot to any failure and to direct his attention to a single central warning panel that announces the nature of the problem.

Problems

- Meanings of specific audio warnings have not been consistent.
- Some aircraft assign a different meaning to the same sound depending on whether the aircraft is on the ground or in flight.
- Audio warnings may be missed by the pilot if they are sounded only once.
- Repeated audio warnings can become irritating and disruptive of communications.
- Warning systems must be reliable and must not generate false alarms.
- Mode awareness must be evident to the pilot. Since automatic flight and engine management systems can be set up in many modes, it is possible for the pilot to believe

that the aircraft is programmed to carry out one function when it is, in fact, performing another.

Intelligent Flight Deck

ELs enable the pilot to access a wealth of information stored on disk. Gomer (1992) mentions that some of the benefits associated with ELs include the use of flat panel display and touch screen technology, incorporation of an airborne data management system, intelligent data retrieval, and the possibility of serving multiple applications. Safety is improved through timely access to important material, data filtering, and data consolidation.

- Features for flight operations encompass paper reduction on the flight deck, workload reduction through features such as automatic checklists for normal, emergency, and expanded operations, customization of the display for features frequently accessed, and storage of sections of flight manuals, operations manuals, and airport analysis manuals.

A favored database arrangement for FMSs is topic oriented. Data integration permits portions of many manuals to be combined to provide information for a specific topic. The system can make use of hyperlinking to provide links to various manuals in sequence.

Special functions have been developed for accessing information. The touch screen can make use of special features such as soft special function buttons, page, scroll, and arrow key functions, zooming, and the ability to display all of a navigation chart. Pilots have shown a preference for graphical displays and a hierarchical menu rather than form filling. The soft keyboard was preferred for one-handed operations. Keyboards were not preferred by pilots. Other data access features of FMSs include search options or going directly to a screen, the ability to place information into a "clipboard area", and a bookmark function for quick retrieval of frequently used information (Gomer 1992).

- Digital technology has made possible the electronic display of navigation chart information. Benefits of electronic navigation charts include (Curran 1992):

- Streamlining revision and distribution,
- Optimizing chart access,
- Highlighting information of interest,
- Decluttering information,
- Extending EFIS present position map concept,
- Facilitating phase transition, and

- Supporting autonomous airplane navigation.

Guidelines for decluttering electronic navigation charts include (Sellers 1992):

- Remove non-essential information.
- Allow the pilot to add or subtract information as needed.
- Prohibit the pilot from changing data, but allow him the ability to select non-mandatory data.
- Include panning and zooming capabilities.
- Select fonts specifically for airline use — for example, use a flat-topped "3". A round-topped "3" could be mistaken for an "8". Use serifs for the letter "I" to distinguish it from the number "1" or a lower case "l".

Stokes and Wickens (1988) present considerations for HUDs. HUDs project attitude information and an artificial horizon on the windshield. Related information such as airspeed and altitude are often displayed too. The purpose is to allow the pilot to acquire information on the HUD instruments without taking his eyes off the outside scene. HUD optics present possible conflicts between near and far. When creating HUD displays, the designer must consider:

- The ability to focus on one domain without distraction or clutter from the other,
- The ability to process information in parallel from both domains, and
- The ability to switch attention between domains.

To communicate with display systems, the pilot must use an input device. Keyboards and touch screens are two common devices. Green (1992) indicates that the flight management computer keyboard is a device that is very difficult to use. The amount of functions being put on this system is increasing and, coupled with the nonstandard character arrangement on the keyboard, makes data input increasingly difficult.

As a result of two touch screen studies, Beringer (1990) recommends that applications have established key input areas. Positions along the lower and right-hand borders of the CDU should be used to minimize activation time and error. The use of the lower border exclusively can accommodate users with either right-hand or left-hand preference. Other variables to consider are:

- Operator's angle of regard,
- Location of the target on the screen,

- Technology type,
- On-screen vs. off-screen input device, and
- Effects of various types of gloves on operator performance.

Leahy and Hix (1990) also investigated touch screens. They found that persons tended to touch below a target, with the touching distance increasing as the target location moved down the screen. Also persons tended to touch towards the sides of the screen.

5.4.3.1 Icons Versus Alphanumeric Displays

Recent research has studied the use of icons versus alphanumerics for cockpit displays. Camacho, Steiner, and Berson (1990) found that reaction times were faster for icons. Possibly this occurred because the icons were a more physically distinct set than alphanumerics. However, alphanumerics are more precise while icons can be ambiguous and confused with each other. Positioning of alphanumerics and icons was also studied. Fixed positions produced faster reaction times and better tracking performance in comparison to random position. Performance was better when the user knew what to expect. Subjective feedback from this study showed preference for icons.

Additional findings indicate (Steiner and Camacho 1989):

- Increasing use of icons adds pictorial realism to displays and aids in pilot comprehension.
- Comprehension of displays must occur rapidly — especially in high information-load situations.
- Few studies investigate what applications can benefit from use of icons and which should continue to use alphanumerics.
- Learning, speed of comprehension, errors, and impact on mission success must be tested before incorporating icons into future cockpits.
- For displays that present only a small amount of information there is no significant difference between display formats.
- As the amount of information presented increases, the use of icons is more effective.
- As the set of display icons increases, it is believed that an advantage would develop for alphanumeric displays presenting a small amount of information.

Camacho, Steiner, and Berson (1990) have identified a number of issues relating to the use of icons versus alphanumerics:

- Using icons may require training. Some formats may be harder to learn, but once learned may be easier to use.
- PVIs that are not standardized between cockpits could cause problems for pilots if they fail to recall the meaning of an ambiguous icon.
- Accuracy/response time trade-off needs to be determined. Alphanumerics may provide more accuracy, but icons may provide a faster response time.
- Parameters of system usage must be investigated before the type of interface format is implemented.

5.4.3.2 Auditory Technology

Although visual displays dominate the cockpit, audio technology also is present. The evolution of automated digital cockpit systems has incorporated audio annunciators. Stokes and Wickens (1988) present advantages, disadvantages, and guidelines for auditory annunciations.

Advantages of audio annunciations include:

- Rapid alerting, irrespective of head position or eye fixation,
- Quick perception of auditory alerts,
- Quick response to audio warnings as compared to similar warnings presented visually,
- No need for adjustment of gaze to receive the message,
- Usefulness in situations where vision is likely to be degraded,
- Less influenced by high acceleration forces, anoxia, darkness, bright sunlight, glare, and vibration,
- May be less costly than equivalent visual displays, and
- Require little or no instrument panel display space.

Limitations of audio annunciations are:

- Overuse can lead to auditory clutter,

- Can be intrusive and distracting and may disrupt concentration,
- May not be optimal for presenting comparison data because of the serial nature of speech, and
- Parts of long messages may be forgotten after or during transmission.

Research findings for speech versus nonspeech annunciation include:

- Complex information is best presented by verbal signals (speech or visual) rather than nonverbal auditory signals (bells, tones, etc.).
- Visual displays, when combined with a speech warning provide a shorter response time than when combined with a nonspeech warning.
- Voice warnings have the potential to be more flexible and informative than simple tone warnings.
- Use of speech is likely to be more effective during periods of workload and stress when meaning of coded signals may be forgotten.
- The simplicity of nonspeech annunciations make their use advantageous under certain conditions.
- Synthetic speech may be masked more in ambient noise than a warning tone.

Nonspeech annunciations are comprised of bells, whistles, horns, buzzers, clackers, and electronic tones. They may vary in pitch, duration, and intensity. Problems associated with the use of nonspeech annunciations are:

- Forgetting the meanings of nonspeech annunciations over time,
- Lack of standardization of nonspeech annunciations among aircraft,
- Similarity among nonspeech annunciations — this can be dangerously confusing, especially in a high workload or stressful situation.

Speech annunciations also can be found in digital systems. Some applications of speech annunciations are to present advisories, status information, and warnings. It was noted that warnings must be received quickly irrespective of eye fixation or workload and must be brief. Speech was preferred by pilots only to transmit urgent information. Preference was expressed for visual presentation of advisory information.

Synthesized speech research has discovered a number of factors affecting intelligibility:

- Method of speech generation,
- Similarity to human speech,
- Speech rate, volume, voice pitch,
- Ambient noise level,
- Size of vocabulary set, and
- Choice of vocabulary.

It was found that synthesized speech was less likely to be confused with flight crew speech or radio transmission, and that compressed speech could help decrease response time. However, synthesized speech generally is less intelligible than human speech and comprehension within a linguistic context sometimes is lost.

Some annunciations include speech and nonspeech combinations. It was reported that a nonspeech alerting tone before a speech message may help the pilot shift attention to the speech message.

Speech recognition systems respond to spoken input. They may be speaker dependent or independent. Speaker-dependent systems must be "trained" to recognize a specific speaker while speaker-independent systems recognize a wide range of speakers (McCauley 1984). A number of variables can affect the design of speech recognition systems (Simpson 1985). These include:

- Characteristics of the user,
- Physical environment,
- Communications environment,
- Operator's workload,
- Constraints imposed by the task,
- Amount of stress on the operator, and
- Speech recognition application.

Simpson (1985) made a number of observations and guidelines from case studies:

- There is variability in human speech under stressful conditions.
- Systems that depend on highly accurate speech recognition input tend to amplify effects of recognition error.
- Regular checks and tests by users are more likely to lead to successful systems.
- For speaker-dependent systems, system training is sometimes more effective when conducted in the context of the operational task.
- Other voice communication functions in the task environment sometimes interfere with the speech recognition task.
- For externally paced tasks, the timing of the task sequence can be disrupted either by long recognition time or recognition error.
- The lack of an appropriate recognition feedback mechanism can lead to confusion about the system status.
- The benefits derived from voice input and output are highly dependent on the specific task and environment.

General guidelines for appropriate use of speech annunciations in the cockpit are:

- When visual warning signals could be missed or obscured,
- When there are too many visual displays,
- When information must be presented independent of head movement or body position,
- When darkness limits or precludes vision, and
- When there are conditions of anoxia, because of the greater resistance of auditory sensitivity to anoxia as compared to visual sensitivity.

Speech annunciations are preferred over nonspeech annunciations:

- When flexibility is required,
- When the message source must be identified,
- When listeners have no special training in coded signals,

- When rapid two-way information exchanges are required,
- When messages deal with a future time, requiring preparation, and
- When stress could cause the operator to forget the meanings of coded signals.

When designing systems that incorporate speech annunciations, designers must consider that:

- Speech requires time to be spoken and may be misunderstood in the presence of other competing voice messages, aural signals, or noise.
- Speech may not always provide the most rapid way of interacting with the system.
- The receiver of the speech message has difficulty processing more than one message at a time thus speech is a single-channel code.
- Messages have a transitory existence unless they are recorded for later playback.
- Speech recognition technology requires a vocabulary of acoustically distinct words.

5.4.4 Additional Resources

A number of documents published by the SAE contain standards for design and placement of cockpit instrumentation. These documents are listed in the bibliography section and discussed in section three of this report.

5.4.5 Design Issues and the National Plan

Objective six of the flight deck section of the National Plan for Aviation Human Factors is to encourage the development of controls, displays, and workstations for aviation application that facilitate the interface between humans and machines. A number of issues associated with cockpit design are expressed in the National Plan:

- Most advances have occurred by applying human factors design principles on a subsystem by subsystem basis. This may have negative consequences since design changes on one system that have been scientifically validated as enhancing operator performance, may well have workload implications for a seemingly unrelated system.
- FMCs — There is a need to standardize some aspects of the FMC interface to simplify training and increase generalization between cockpits.
- Keyboards — Current advanced technology aircraft cockpits often contain a variety of data entry keyboards for use in programming and operating flight automation, navigation,

and communication systems. Keyboards are input devices prone to high error rates and variations in keyboard design may contribute to even higher error rates.

- Cockpit Differences — Pilots frequently operate similar aircraft with only small differences in cockpit displays and controls. The effect of these small differences are not known but potentially could lead to critical errors and safety hazards.
- Display Compression — One method of adjusting to display failure in glass cockpits is to represent the lost display on the remaining CRTs through overlaying or display compression. The useability and safety of using these altered displays either in a failure mode or routinely is not known.

5.5 Crew Workload and the Pilot-Vehicle Interface

5.5.1 Definition

Workload can be considered the demands of a task. It is the "work" that is "loaded" onto an operator. Imposed workload involves factors such as task objectives, environmental variables, task structure, temporal organization, system resources, operator qualifications, and incidental variables that may make task performance substantially different from one instance to the next. Perception of task demands, operator capacity, and operator behavior are operator variables that also affect workload (Hart 1984).

5.5.2 Workload Assessment and Measurement

5.5.2.1 The Importance of Workload

The assessment and measurement of workload has played an important role in the development of automated, digital cockpits. Workload can be used as a predictive tool during new system development to ensure that the pilot will have sufficient spare information processing capacity to cope with failures or unexpected events.

Workload assessment techniques can be used to identify and assess the source of temporary bottlenecks which may occur in the system when the demands of a task exceed the capabilities of the pilot and performance degrades.

Workload assessment can be used to compare two alternative pieces of equipment or to enable comparisons to be made between individuals. In addition, workload can be a factor for evaluation of new cockpits, changes to systems, or operating procedures, aircraft certification, and the determination of crew complement (Green et al. 1991).

Safety is another area in which workload plays an important role. Workload is an important factor in causing human error (Kantowitz and Sorkin 1983). Humans are most reliable under

moderate levels of workload that do not change suddenly and unpredictably. Extremes of workload increase the likelihood of human error.

Crew size also is impacted by workload. While two-pilot crews are now routine, it is questioned whether the reduction in crew size from three to two has been at the expense of higher crew workload. With only two crew members, the need for communication among crew members may be increased. If there is not sufficient workload for a third crew member, the work underload can increase human error.

Automation offers the potential for both decreasing and increasing crew workload. Automation can result in a decrease in workload, but opportunities for system error may not decrease correspondingly, since automation can introduce large delays between the performance of a crew action and its ultimate effect (Kantowitz and Casper 1988).

5.5.2.2 Workload Assessment and Measurement Techniques

The Aircrew Performance Measurement section of the National Plan for Aviation Human Factors (1990) describes operational problems. One problem has been the development of standardized instruments for measuring workload.

Measuring workload, in particular cognitive workload, has provided a challenge to the human factors community. While many methods of measuring and predicting operator workload exist, the relationship between measures of imposed task demands, and measures of performance remains complex and contradictory. Even when workload and performance can be measured, interpreting the measures remains difficult. It is not clear how much workload is "too little" or "too much" (Hart 1990).

While physical workload can be defined and measured in terms of energy expenditure, mental workload measurement is not as easy or precise. Kantowitz and Caspar (1988) review some methods of measuring mental workload including subjective ratings, secondary tasks, and biocybernetic indices.

Subjective ratings ask operators to rate how hard they have worked in a task during or after the task has been completed. Advantages of this form of measurement are its ease of implementation and nonintrusive nature. Disadvantages include a lack of theoretical framework, difficulties in comparing results between experimenters using different rating scales, ratings which yield relative rather than absolute results, and problems of applying valid statistical tests to data obtained from subjective ratings.

Secondary tasks are another form of measurement. This method loads an additional task on the operator in addition to the main task and measures performance on the extra task. Decrements in performance of the secondary task are thought to indicate increased mental workload in the primary task. Advantages of this approach are objectivity, and a strong theoretical background.

However, this approach is obtrusive in operational settings, and problems can arise in comparing data from different experiments using different secondary tasks.

Biocybernetic measures use dependent variables such as heart rate, pulse wave velocity, skin temperature, and pupil diameter. This type of measure has been found to be superior to subjective ratings in objectivity and superior to secondary tasks in its unobtrusiveness. Disadvantages of this approach include continuous monitoring, which generates an enormous amount of data, sometimes embedded in a great deal of biological noise. Lack of sound theoretical framework makes interpreting the results from this measure a difficult task (Kantowitz 1988).

5.5.3 The Effects of Automation on Workload

While one of the goals of automation is to reduce workload, studies have found that automation realigns more than relieves it. Workload is reduced at cruise altitude but during climb or descent into a terminal area, workload is increased. Wiener conducted a simulator study using 12 Delta crews flying a McDonnell-Douglas DC-9-30 and 12 Delta crews flying an McDonnell-Douglas MD-88 (Hughes 1992). The study tested the reactions of two-man crews in the traditional McDonnell-Douglas DC-9 versus the highly automated McDonnell-Douglas MD-88. The crews flew a route that included mechanical problems and deteriorating weather conditions during a missed approach into a nonpublished holding pattern. The McDonnell-Douglas DC-9 and the McDonnell-Douglas MD-88 crews made about the same number of errors. However, in self-evaluations, the McDonnell-Douglas MD-88 crews reported a higher workload than the McDonnell-Douglas DC-9 crews. Wiener reported that the study failed to find reportable difference between the McDonnell-Douglas DC-9 and McDonnell-Douglas MD-88 crews, and thus at this point no inferences could be drawn about the effect of cockpit automation on the ability of qualified crews to fly a difficult mission. There was insufficient evidence to support the hypothesis that automation would generate more serious errors.

In the past, many pilots were required to use all automated systems. Now, some operators are encouraging pilots to use their own discretion in choosing to use automated systems or flying in manual mode. Wiener's study found that pilots who used a combination of automatic and manual flying were most successful.

The McDonnell-Douglas MD-11 uses a bank of automatic controllers to run the hydraulic, electrical, pneumatic, and fuel systems and to accomplish checklist tasks for the pilot rather than presenting a series of tasks to be performed by the human operator. The idea is to capture all the "guile and cunning" of a human flight engineer in the software, but to keep the pilot informed of what is happening (Hughes 1992).

Hart and Sheridan (1984) report that automation is only one of many ways to achieve acceptable levels of workload, reduce errors, and improve or enhance performance. Other methods such as revised procedures, training, and improved system design might be alternatives to additional automation. The technical feasibility of automating a function should not be the only reason for

doing so. The use of automatic intelligent machines will not necessarily reduce the amount of work that humans do, but may permit the enhanced performance of more and more complex tasks. The explosion of automation will continue, but its pace and design should be tempered by understanding of and concern for human workload.

Maher (1992) presents the possibility of cognitive overload in present automated cockpits. He reports that the present generation of automated aircraft has reached, and in some cases, exceeded the biological barrier of the human operator's cognitive limitations. Task overload is the primary cause. Cockpit overload is brought about by either extreme information processing demands or excessively complex SOPs to operate the automation during busy stages of flight.

Concern was expressed about the lack of a scientifically based philosophy of automation which describes the circumstances under which tasks are appropriately allocated to a machine or to the pilot (Henderson 1992). Short-haul, high-density operations were identified as an area in need of workload control. Also, the use of data link and better design of the man-machine interface would be beneficial. Workload control can benefit by making existing technology easier to understand and harder to misunderstand.

5.5.4 Attention and Workload

Attention can be thought of as a dimension of conscious awareness and active mental power (Edwards 1990). Selective attention is the process by which inputs are sampled to ensure that the information which receives detailed processing is relevant to the task at hand. It is possible and sometimes beneficial to divide attention between tasks. For example, a pilot flying a visual approach will be required to divide his attention between looking ahead outside the aircraft and looking down at the airspeed indicator. Becoming consumed by one task can lead to error.

Stress can influence attention. The level of arousal influences the scanning pattern of an individual. For example, during the quiet period of the cruise portion of flight, when arousal is low, a pilot does not scan the instruments as frequently as he does during the approach and landing phase when arousal level is significantly higher. Under conditions of high stress and arousal the sampling rate may increase but the pattern of sampling is reduced to a narrower range of stimuli as a consequence of attention being restricted to the primary task. Important information could be missed in an emergency situation because a stress situation caused a pilot to restrict his attention to the primary source of a problem.

Vigilance

Vigilance is another factor affecting attention. Over time there often is a decrease in signal detection (Edwards 1990). This can be prevented by:

- Adequate rest periods,
- Feedback of performance on each signal,

- Breaking the monotony with some other activity, and
- Making the signal more noticeable (brighter, louder, etc.).

Behaviors can be changed to reduce the number of missed signals through proper training (Green et al. 1991).

Mollard, Coblenz, and Cabon (1990) found that there is a decrease of vigilance during periods of low workload. Often the co-pilot or flight engineer experienced this low period at the same time as the pilot.

Information and Eye Focus

Typically, people tend to focus on elements of a scene that contain significant information. These significant elements have detail that is unusual or unpredictable, or they reflect meaningful aspects of the scene. There is a tendency not to look at things that do not change, are of uniform texture, or blend with their surroundings (Edwards 1988).

Scanning

A pilot's skill of scanning can be altered by additional mental workload. Some findings are (Edwards 1988):

- With extensive training searchers report that they do not see nontargets and that the targets stand out from the rest of the scene.
- With practice searchers reached a very high level of stable performance.
- It is quicker to search for a target than determine its absence.
- The greater the contrast between the target and its background, the better the search.
- Color is the best cue for targets, size is next, shape is poorest.

Detection Problems

Detection is noticing that something has changed then properly diagnosing the cause and implications of the change. While principles of signal detection, perceptibility, and instrument significance will affect how soon a problem is detected, prevention and remedy for detection problems lies in strongly ingrained instrument scan.

Studies found that individual pilots search for information differently during a diagnosis and that some pilots have the same kind of systematic search pattern for all kinds of problems (Edwards 1988).

5.5.5 Workload Issues and the National Plan

The National Plan for Aviation Human Factors (1990) has identified a number of issues related to workload as areas in need of study. The shutdown of automatic systems is one area. The Plan mentions that "cognitive workload may be generated when a flight system is shut down by the FMC and the flight crew is not informed of the reasons for the shutdown. The extent of this workload increase should be determined and considered in the design of cockpit systems and procedures. This may require the development of workload assessment methodology specific to this problem."

Developing a valid methodology to measure and predict pilot workload is another issue presented in the National Plan. Related to certification, the FAA is concerned with "developing a method for determining underload, overload, optimum workload, and corresponding management strategies to maintain the highest level of safety under adverse workload conditions."

5.6 Crew Resource Management, Training, and the Pilot-Vehicle Interface

5.6.1 Communication in the Cockpit

Chidester and Foushee (1989) conducted a study in which three captain personality profiles were identified. Captains with high achievement motivation and interpersonal skills were identified as Instrumental-Expressive (IE+). It was found that these captains were consistently effective and made few errors. Captains with low achievement motivation and a negative expressive style were called Negative-Expressive (Ec-). They made more errors and showed less crew coordination during the study period. The third personality profile, Negative-Instrumental (I-), belonged to captains who were highly competitive, verbally aggressive, and impatient. The I- captains were less effective initially, but were equal to the IE+ captains over time.

Orasanu (1991) examined communication behaviors that distinguish between more and less effective captains. The study was based upon data collected from the Chidester and Foushee (1989) simulation study. It was found that captains fitting the EI+ and I- profile used language differently from Ec- captains. Crews headed by I- and IE+ captains talked almost twice as much overall as the Ec- crews. This pattern held for normal and abnormal flight phases. During the abnormal phases of flight EI+ and I- captains talked more about what to do and engaged in problem solving talk.

During normal phases of flight, patterns of talk in the categories of problem recognition, goal setting, alerting/predicting, explaining, coordination, commands, and monitoring status were similar among IE+ and Ec- captains. However, during abnormal phases of flight, patterns of talk associated with coping with the crisis and CRM showed differences.

During emergencies, effective captains articulated plans and were explicit in specifying when certain actions were to take place, and in coordinating their efforts with those of their crews.

It was found that the more effective captains stated their intentions and made contingency plans in advance. They gathered more information and were better prepared for emergency situations.

Straus and Cooper (1989) examined the interaction of technological and social factors and their effect on group communication. They found that willingness to exchange information in the cockpit is a precursor to effective crew performance and coordination. However, crew members often are not willing to exchange information freely. Characteristics of group structure can inhibit the kinds of communications that facilitate effective performance.

It was found that under automated control, crews that exchanged a higher ratio of task-relevant to task-irrelevant communication performed better. Homogeneous crews (crews with similar rank and experience) were more communicative in general, than heterogeneous crews (crews with mixed rank and experience), but heterogeneous crews demonstrated superior automated group performance and communication patterns.

Wickens (1989), however, found that flight performance differs little as a function of crew composition (homogeneous vs. heterogeneous).

5.6.2 Crew Interaction and the Cockpit

Foushee and Helmreich (1988) compiled an overview of group interaction and flight crew performance. Group performance factors are comprised of input variables, group process variables, and outcome variables. Input variables are the personal characteristics individuals bring to the group, characteristics of the group itself, and factors related to the environment or the task performance situation in which the group is functioning. Process variables refer to the dynamics of group interaction or how group members communicate with each other. Output variables relate to how well the group performed the task, as well as other outcomes indicating how group members feel about each other and what they have learned as a result of the interaction.

Input variables encompass several factors. Individual factors include skills, physical state, attitudes, and personality characteristics. Group factors include elements such as group size, prior history, structure, composition, and cohesiveness. Environmental factors are the characteristics of the task, reward structure, situational aspects such as level of stress associated with performing the task, task design, and attractiveness of the task.

Group process variables include delegation of responsibility, style of communication, communication hierarchy, and patterns of communication.

Output variables constitute task performance factors such as quality, time necessary for performance, number of errors, group cohesion, and member knowledge. Skill, attitudes, motivation, task characteristics, reward structure, and other input factors are modified depending on prior performance outcomes.

Leadership profile studies identify two basic types of leadership profiles: task-oriented and group-oriented. Task-oriented leaders primarily are concerned with performance while group-oriented leaders focus upon the feelings and needs of group members.

It was found that the most effective leadership type is dependent upon the type of group and the task with which the group was charged. However, the two profiles are not viewed as mutually exclusive. It is possible to possess high levels of both, low levels of both or to be high in one dimension and low in the other. Research has suggested that "low task, high group" oriented managers are effective in routine situations, but not as effective in performance situations with high task demands. "High-task, low-group" oriented managers may be effective in situations of high task demand, but not as effective in day-to-day operations.

Incident and accident records imply that lack of effective interpersonal skills affect the group process of information exchange. Subordinate crew members report intimidating and insensitive captains and indicate that they hesitate to speak up even in potentially dangerous situations. The inherent danger of this situation is that subordinate crew members will become conditioned not to speak up even when there is no reason to suppress input.

Role hierarchy or structure is another input factor affecting the flightcrew group. In airlines, position is often a function of seniority and experience. The person in charge usually is the one with the most experience. Role structure is well-defined and governs how subordinates interact with superiors. This may explain why subordinates are hesitant to speak up. Problems arise when air carrier mergers take place and formerly senior captains are now at the bottom of the seniority list.

Attitude toward cockpit crew coordination has been shown to be an important input factor. Effective managers felt they were not infallible and encouraged other crew members to question their actions when necessary. They also recognized a need to be sensitive to the feelings of others and to verbalize intentions so that crew members were aware of necessary information.

Ineffective managers advocated a more authoritarian style of management, and were not as quick to acknowledge their own limitations.

Flight crew performance seems to hinge on both the quality and quantity of communication. When more information about aspects of flight status are transferred, fewer operational errors appear. When complete coordination or sharing of strategic plans takes place, a negative factor can surface. In groups where interpersonal relations are strained or where there is too much agreement, information discrepant with the group's course of action may be ignored or de-emphasized, even when the information is critical.

Crews in which commands, inquiries, and observations are frequently acknowledged experience fewer errors. Acknowledgements served a validating function and are reinforcements to the input of other crew members. It has been suggested that patterns of communication can serve to increase group member effort and encourage further participation in the group process.

Crews in which commands such as those associated with power settings, speed limits, altitude deviations, and transfer of control between the captain and first officer were issued experienced a lower incidence of flying errors. It appears that communication of this type seems to assure proper delegation of cockpit duties and facilitates coordination and planning. However, it has been found that overuse of command statements could have a negative effect. Accurate communication has been shown to be critical to group process in flight crews. Incidents from the ASRS database report cases where crew members thought they understood the intentions of other crew members but in reality did not.

A number of observations were made about flight crew output. Crews who had flown together communicated more overall. They issued more commands (both pilot and co-pilot), made more suggestions and statements of intent, and indicated more willingness to share information. There were more acknowledgements of communication between crew members who had flown together and more disagreement was expressed by first officers. There was more nontask related conversation in crews who had not previously flown together. Significantly more tension release was shown and more frustration was expressed among captains who had not flown with the same first officer before. A negative aspect of flying with the same crew all the time was complacency and boredom.

O'Hare and Roscoe (1990) examined cockpit management styles. They found that pilots who were rated effective in cockpit management were likely to possess these attitudes:

- Recognition that their personal decision-making abilities would be degraded in an emergency situation,
- Willingness to have crew members question decisions, and
- Favorableness to open discussion of personal stress or problems and the creation of a harmonious atmosphere on the flight deck.

Poor cockpit managers were likely to deny personal limitations and resent active involvement of crew members during an emergency.

5.6.3 Crew Resource Management and Safety

The National Plan for Aviation Human Factors (1990) indicates that there is a need for improved Cockpit Resource Management (CRM) to enhance safe operations. The importance of the cockpit social environment is stressed. The social environment is defined as flightcrew coordination, or cockpit resource management. (More recent literature favors the term Crew Resource Management in place of Cockpit Resource Management.) The Plan states that "the effect of the social environment on the crew's interaction has been demonstrated to have a significant impact on the crew's ability to perform the job safely and effectively."

Many errors in the cockpit can be traced to how the crew worked together as a team. Accident analysis reveals that often one member of the crew may have possessed crucial information but this information was not effectively communicated to the rest of the crew. CRM is based on the observation that crews who were the most effective in coping with simulated malfunctions in full mission research studies were those who communicated most.

One goal of the communication is to be certain that the entire crew is in agreement about the situation of the aircraft and the approach to resolving an inflight problem. The main means of achieving crew situational awareness is through explicit verbal communication (Palmer 1990).

Flight deck management involves coordinating a small, highly task-oriented group. Many separate actions are required even for routine flights. Actions including checklist items, callouts, configuration changes, and transferring flight controls from one pilot to another involve crew coordination (O'Hare and Roscoe 1990).

Studies have found that instrument or system failures were detected and diagnosed within a range of 0.5 seconds to 40 seconds, with an average of 10 seconds. However, in a simulation in which the pilot feigned incapacitation, the detection and reaction time ranged from 30 seconds to four minutes, with an average of 1.5 minutes.

In the past emphasis was placed upon individual performance. Most airlines now place some emphasis upon crew coordination procedures. All crew members are required to monitor and cross-check the actions of the other crew members.

5.6.4 Pilot and Crew Training

Pilot and crew training has changed since the early days of aviation where a pilot trainee for the French Foreign Legion received ground lectures then was left on his own to master basic airplane maneuvers. This trial and error method destroyed many planes, and resulted in a high trainee injury and death rate (Caro 1988).

Today flying skills as well as crew coordination are emphasized in training. Pilot trainees may take part in full mission simulation or may learn difficult tasks through part-task training. Trainees may receive instruction in a classroom from a human teacher, independently using a computer-based or Intelligent Tutoring System (ITS), or in an airplane simulator complete with motion, communication with ATC, and realistic flight instruments. Many operations too difficult or dangerous to perform in the air, now can be mastered on the ground through simulation. The potential for thorough and safe pilot and crew training is within grasp.

5.6.4.1 Crew Resource Management Training

A typical CRM training course is multi-day and provides experiential learning in interpersonal communications, leadership, decision making, conflict resolution, stress and stress management, and related topics. Helmreich and Wilhelm (1991) studied the outcomes of CRM training. The

study focused on self-report evaluations of an initial CRM seminar and attitudes regarding flight deck management and personal capabilities. Participants were more than 15,000 crew members from 12 airlines and military organizations.

Relevant findings of the study are:

- For seminars held within one airline, favorable reactions to sessions differed significantly between sessions. This suggests that standardization in impact is not being achieved. Each organization studied replicated this finding. Content, instructors, group mix, background and experience levels, and initial attitudes were not found to be significant causal factors. It was hypothesized that the reactions were a function of idiosyncratic group dynamics, such as an especially charismatic person within the group.

Research goals in this area should be to gain a better understanding of group dynamics operating in good and less effective seminars and to determine whether facilitators can be trained to recognize when seminars are going astray and take effective action to counteract such tendencies.

- The organizational culture had a measurable effect on attitudes.
- Significant differences in pretraining attitudes between airlines and between crew positions within each organization were found. This finding indicates that different organizations have developed their own cultures and norms despite operating in a highly regulated environment that stresses standardization.
- Since differences persist after initial awareness training it appears that cultures and subcultures are difficult to change. It is not likely that individuals who hold divergent views regarding how individuals and crews should function can form optimally effective teams.
- Although overall findings portray highly significant positive change, some individuals experienced a boomerang effect or a change in the direction opposite of that intended. Those who most need the training may be less likely to be influenced in the desired manner. Individuals with personality deficits in the areas of interpersonal capabilities may feel threatened by the emphasis in training on the importance of communications and human relations skills.

If the boomerang effect persists, training needs to address working effectively with difficult peers.

Organizations need to face the issue of dealing with CRM failures. It must be determined what individual crew members and organizations should do when confronted with the individual who poses a continuing threat to safety because of poor resource management practices.

This problem is reflected in the National Plan for Aviation Human Factors. The section on Training and Selection describes problems associated with the role of individual differences in the effectiveness of CRM training programs. It indicates that "crew members with particular personality constellations and attitudes have proven resistant to traditional CRM training approaches. Research is needed to identify more clearly the personality traits and/or attitudes that interfere with individuals' benefiting from CRM training."

5.6.4.2 Line Oriented Flight Training

Line Oriented Flight Training (LOFT) was designed to augment existing simulator training, by providing training in a realistic environment. Training crews fly a full simulated trip in real time. Sessions are as authentic as possible and include a normal pre-flight briefing, full trip paperwork, and external communications. The session may be videotaped. After the session, debriefing takes place in which emphasis is placed on crew coordination and communication.

The purpose of LOFT programs is to heighten individual awareness of group process and make crew members aware of factors that can influence their behavior as members of the group (O'Hare and Roscoe 1990).

Strickler (1982) citing the findings of NASA/Industry Workshop (1981) compiled characteristics of LOFT:

- LOFT applies line-operations simulation to pilot training programs.
- LOFT involves a full crew complement. Each crew member operates as an individual and as a team member in the same manner as he would during line operations.
- LOFT involves simulated real-world incidents unfolding in real time. The consequences of crew decisions and actions during a LOFT "flight" will accumulate and impact the remainder of the trip in a realistic manner.
- LOFT presents problems that may have a number of acceptable solutions. Handling problems is a matter of judgement and decision making.
- LOFT requires effective interaction with, and utilization of all available resources.
- LOFT is a training and learning experience in which errors probably will be made. It is not a checking program in which errors are not acceptable.

A number of cautions for LOFT programs were:

- LOFT will not solve all training problems.

- LOFT is resource management training but it is not skill training. Manual skills are a prerequisite.
- LOFT will succeed only as part of a total training and crew education program that ensures basic knowledge and skill norms are met.

5.6.4.3 Part-Task Training

Part-task training involves practice on some set of elements of the whole task as a prelude to performance of the whole task. Part-task training is intended to improve learning efficiency and reduce the cost of training. This type of training is used effectively with difficult tasks that can be partitioned into relatively independent components.

Three types of part-task training have been identified: segmentation, fractionation, and simplification. Segmentation can be used when subtasks have identifiable endpoints. Subtasks are practiced in isolation or in small groups, then they are recombined into the whole task. For example, pilots may learn parts of a landing task and successively add more parts until the whole procedure is learned. An advantage of segmentation is that more time can be spent mastering the difficult portions of a task without spending time on parts that are easier to learn or already accomplished.

Fractionation manipulates two or more subtasks that are executed simultaneously in real time. Independent practice on pitch and roll before these subtasks are combined for straight and level flight is an example of fractionation.

Simplification is a procedure in which a difficult task is made easier by adjusting one or more characteristics of the task. Simplification is used with greatest advantage for tasks that are too difficult to allow learning to progress or are so difficult that learning is slowed. Skills learned with the easy version of the task might be applied to learning the more difficult task.

Part-task trainers offer potential cost savings for flight training by allowing critical subskills to be learned on relatively inexpensive devices (Wightman and Lintern 1985).

Factors contributing to the value of part-task training are (O'Hare and Roscoe 1990):

- Providing training at a lower cost than whole-task training,
- Providing additional training in individually critical tasks: for example, special types of landings,
- Providing training in new task elements to pilots with considerable previous experience: for example, in type conversions, and

- Providing recurrent training in infrequently encountered maneuvers and procedures: for example, failed engine landings.

5.6.4.4 Embedded Training

Embedded training refers to the use of operational equipment that is in a training mode rather than an operational mode. Embedded training uses hardware or software features of a particular aircraft or system provided specifically for purposes of training or testing. Embedded training uses application software that enables the aircraft's electronic systems to operate independently of current conditions or to simulate training events. Embedded training features of an aircraft may be designed for use during flight or on the ground. Examples of embedded training are found mostly in military applications such as mission rehearsal, air-to-air combat, and air-to-ground weapons delivery (Caro 1988).

5.6.4.5 Computer Based Training, Intelligent Tutoring Systems, and Simulation

The National Plan for Aviation Human Factors has presented an issue stating that

...current systems for training delivery are outmoded and inadequate to meet the training demands of the future. Moreover, modern training technology (e.g. automated design systems, interactive training simulation) is not available at a level to meet current and future training needs. Clearly the need exists to address the effectiveness of simulation in training and to consider the development of diagnostic instruments and remedial training. Research must also address the utility of augmenting simulation with artificial components such as expert systems and intelligent tutoring. Key to the success of these automated training aids is the specification of learning objectives and learning strategies relevant to the use of various levels of simulation.

Computer Based Instruction (CBI) permits instruction to be individualized and self-paced. Some advantages of CBI include (Jensen 1982):

- Ability to accommodate a wide variety of student responses and proceed accordingly,
- Capacity for practice and feedback,
- Capability of branching to other areas of the instructional program,
- Ability to specify level of difficulty,
- Possibility of individualizing instruction,
- Ability to include complexity, realism, and time constraints in the instructional program,

- Ability to provide instruction not encumbered by instructor-student personality clashes or ulterior motives,
- Possibility of providing instruction without the presence of a teacher — although it may be beneficial to have one available for consultation, and
- Capacity to standardize instruction across a wide area.

While CBI offers a number of advantages, it does not emulate the skills of an expert instructor by adapting the simulation or level of task difficulty to that of the student, identify and correct misconceptions, or choose analogies to explain complex concepts (Caro 1988). This is the realm of AI.

AI seeks to emulate the behavior of an expert. It applies rules, "learns" by experience, and solves problems not anticipated by programmers, knowledge engineers, and subject matter experts (Caro 1988).

Intelligent Tutoring Systems make use of AI. They are designed to include an instructional environment, a student model, an expert model, and an instructor model. The student's performance is logged and compared to that of the subject matter expert. The ITS provides remediation and instruction based upon comparison between student and expert actions. ITS technology can be combined with simulation to produce a high level of instruction (Johnson and Norton 1991).

Cockpit simulation can range from simple cardboard mock-ups to elaborate training devices that attempt to replicate all aspects of flight. Simulation allows dangerous maneuvers and a range of exceptional or unlikely conditions to be practiced on the ground. Instrument flight and emergency drills also can be practiced safely on the ground. Simulator training can save fuel costs and loss of revenue caused by removing a plane from service for purposes of training. For initial training, low cost simulators effectively deliver high "transfer of training" (O'Hare and Roscoe 1990).

Simulation has been used in pilot training since the early days of aviation. The French Foreign Legion discovered that flight training could be made more efficient by using a plane with little or no fabric on its wings. Students used these planes to practice aircraft handling while taxiing without becoming airborne.

Simulator design is based upon the transfer of training theories of Edward L. Thorndike and Charles E. Osgood. Transfer of training is the effect that learning one skill has on learning a second skill. Positive transfer occurs if learning the first skill makes it easier to learn the second. Negative transfer occurs when learning the first skill makes learning the second more difficult. Thorndike's theory of common elements suggests that transfer will occur to the extent that the simulator and the equipment simulated share common elements. Osgood's concept of transfer surface extends the common elements theory. According to Osgood's theory, where there is a

one-to-one correspondence transfer of training will be high and positive. Less than one-to-one correspondence will decrease the amount of transfer. As technology advanced, simulators became more realistic and accurate.

A number of factors present in simulator training contribute to transfer of training. Cues are the means by which pilots assign meaning to stimuli encountered during flight. Pilots depend upon cues to assess the status and condition of their aircraft, to initiate action, to guide performance, and to signal when an action should be changed or ended.

Cue interpretation and making responses to cues involves discrimination. Discrimination assigns a meaning to a stimulus or response to make it different from others. For example, a pilot learns to discriminate between similar annunciator lamps.

Generalization is a concept that refers to the use of previously learned skills in situations that are different from the situations in which the skills were learned.

Early flight simulators were used primarily to teach instrument flight. The device was made to look like an airplane, complete with wings and a tail. As aircraft became more complex, simulators were designed to correspond to specific aircraft. With the introduction of digital computer technology in the mid-1960s, it became possible to create more realistic simulation of flight dynamics and aircraft system performance (Caro 1988).

5.6.4.6 Recurrent Training

Recurrent training allows pilots to maintain their flying skills. The Air Line Pilot's Association (ALPA) has made recommendations for improved recurrent training:

- Recurrent pilot training should be conducted on an annual basis in an approved flight simulator.
- Flight simulator training should include a review of instrument approaches and selected abnormal and emergency procedures.
- Training should be designed to represent realistic line operational concepts with emphasis on crew coordination.
- Training may include selected weather, wind shear, turbulence, and unusual approach conditions, or other circumstances that are likely to cause accidents.
- Annual training for flight deck crew members should include appropriate review of aircraft systems, aircraft performance, and emergency procedures, including ditching if over water.

- Annual training for flight deck crew should include a review of recent or recurring problems for the aircraft type and additions or revisions to the navigation and instrument equipment or traffic control procedures.

5.6.5 Crew Resource Management Issues and the National Plan

The National Plan for Aviation Human Factors (1990) identifies a number of issues in the area of training:

- Development of objective measurement for these CRM skills:
 - communications,
 - situation awareness,
 - problem solving/decision making/judgement,
 - team management,
 - team review, and
 - interpersonal skills.
- Identification of the critical elements of novice pilot training,
- Determination of the role of individual differences in the effectiveness of CRM training programs,
- Evaluation of the effectiveness of CRM training programs, and
- Evaluation of the effectiveness of LOFT for enhancing CRM training.

6. CONCLUSIONS

The Pilot-Vehicle Interface should be treated as any other aircraft system. No failure mode at this interface can be taken lightly. Formal and comprehensive engineering from initial concept to completion is necessary. The design of the cockpit does not stop at the panels. Design techniques that include the complexities and variables associated with human characteristics in relation to highly integrated digital computers, are required.

Improvements to flight safety can be made in several key areas. They are:

- Developing certification requirements that include human factors,
- Requiring cockpit specifications that address all aspects of the PVI,
- Integrating the human in all areas of the PVI technology,
- Generating methods of verification and validation of the PVI, and
- Using design tools that are flexible enough to include all facets of the PVI.

More economical operation of aircraft and resolutions to the problems presented by overcrowded airways can be addressed by new and innovative technology. To make flight safer, however, the solutions should not raise new problems. New and unique failure modes presented by new technology need to be considered carefully along with their solutions. Cockpit automation needs to consider a multitude of human factors.

Safety is at the heart of human factors and the PVI. The National Plan for Aviation Human Factors represents a massive effort to identify and coordinate human factors research in the field of aviation. In addition to outlining issues and problems and providing specific objectives, the plan also cites work in progress. This is a valuable document for guiding research and preventing duplication of effort. As the National Plan is implemented, it will be interesting to observe the impact of research it generates on the design and safety of cockpits.

Improved safety, economy, efficiency, and performance have been cited as reasons for automating the cockpit. Of major concern is implementing automation to a point where the pilot is "out of the loop." When automatic systems assume most control functions, the pilot's chief role becomes that of a monitor. Among the risks of this situation are loss of aviation skills, boredom and complacency, inadequate preparation to deal with system failures, and loss of job satisfaction. Key questions in this area are which functions should be automated and to what degree should the cockpit be automated. Keeping the pilot informed and aware of the status of the aircraft while reliably assisting the pilot with control functions must be a goal of human-centered automation.

The modern aircraft cockpit is an information-rich environment. While it has become more common to involve pilots and human factors experts in the design phase, the challenge remains to determine the specific information required by the pilot, and how this information is to be organized, presented, and retrieved. Today's aircraft may be easier to fly, but they require more skill to manage. The complexity of and interaction among subsystems further complicates system design. In addition, design revisions beyond the initial stages have become quite costly. Rapid prototyping, intelligent design systems, and simulation currently offer means of trying out designs before they are put into production. The pilot must be involved at all stages of the design process.

One aim of human-centered technology in the cockpit is to assist the pilot during periods of high workload. Accident and incident reports cite extra workload involved with programming the FMS computer in the terminal area as a hazard to safety. Flight crew members report being "mesmerized" by attempts to correct problems with new digital systems. At the other extreme, boredom and complacency are reported as problems during periods of low workload. Either extreme poses a threat to aviation safety and is an issue to be considered seriously by system designers.

Two areas of training are especially important to the PVI: airmanship and CRM. Knowing how to fly aircraft equipped with digital systems, how the systems work, and what to do when the systems malfunction are training issues germane to aviation safety. CRM deals with communication and group process in the cockpit. With digital systems, each computer entry and crew action can result in serious consequences. CRM must train crew members to communicate effectively and clearly and to work as a cooperative group.

Keeping pace with technology is a certification challenge. As part of the Cooperative Engineering Program, the SAE serves industry, government, and the public by developing guidelines and standards for design, manufacture, testing, quality control, and procurement. To advance the state of technical and engineering sciences, the SAE publishes ASs, AIRs, ARPs, and other documents. These documents are advisory in nature and provide a source for related PVI information as well as references to other reports, standards, and regulations. The ARPs are updated approximately every five years. With constant addition of new documents and updates to old ones, the SAE provides a reliable source for PVI-related information.

Newer technology does not necessarily mean better technology and automated does not necessarily mean easy to use. New technologies need to buy their way into the cockpit by using less power, taking up less space, and weighing less, lowering costs, increasing availability, reducing maintenance, and receiving general acceptance by the flight crew. Above all, new technologies need to contribute to the safe operation of the aircraft.

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GLOSSARY

ANISOTROPIC. Having different, direction dependent, physical characteristics.

ATTENSON. A unique sound used on the flight deck for alerting the flightcrew of warning, caution, and advisory conditions.

AVIONIC. Electronic equipment used in aircraft.

BIREFRINGENCE. The splitting of light into two components, where each component travels at a different velocity.

CHOLESTERIC. A liquid crystal phase with molecules parallel to each other but twisting slightly from layer to layer.

COMBINER. A screen designed to reflect selected wavelengths of light while remaining transmissive for others.

DATA BUS. One or more wires or optical fibers that carry signals that represent information.

DICHROIC. Having different light absorption characteristics based on incident polarization direction.

DIELECTRIC. Having an insulating property with respect to an electrical field.

FEDERAL AVIATION REGULATIONS. Subchapter C of the Code of Federal Regulations (CFR), Title 14, Chapter 1.

GETTER. A metal alloy used in a vacuum tube to absorb residual gasses.

GRAY SCALE. A series of tones, varying from black to white.

HERMETIC. Having an airtight seal.

ISOTROPIC. Having the same physical properties in all directions.

LINE REPLACEABLE UNIT. An electronics unit that is made to be replaced on the flight line, as opposed to one that requires the aircraft be taken to the shop for repair.

MONOLITHIC. A single substrate used for an integrated circuit.

NEMATIC. A liquid crystal phase with molecules having a single optical axis in line with an applied magnetic field.

PHOTOLITHOGRAPHY. An integrated circuit fabrication technique using photographically produced masks.

PIXEL. The smallest picture element of a display.

PHONEME. The smallest elements of speech.

RASTER. A pattern of parallel electron beam scan lines used for uniform coverage of a CRT screen.

SENSOR. Any transducer that converts the measurement of a physical quantity to an electrical signal.

SERIF. A fine line finishing off the main strokes of a letter.

SIMULATION. An approximated representation of the behavior of a system with a similar system.

SMECTIC. A liquid crystal phase with molecules arranged in layers.

STROKE. A nonuniform technique of CRT screen refresh using penlike control of the electron beam.

TRANSPORT AIRCRAFT. Aircraft used in interstate, overseas, or foreign air transportation.

ACRONYMS AND ABBREVIATIONS

Å	Ångstrom
A ³ I	Army-NASA Aircrew/Aircraft Integration
ABET	Aerospace Behavioral Engineering Technology
ac	Alternating Current
AC	Advisory Circular
AD	Alerting Display
ADF	Automatic Direction Finder
AI	Artificial Intelligence
AIR	Aerospace Information Report
ALPA	Air Line Pilot's Association
AM	Active-Matrix
AMS	Aerospace Material Specification
ARP	Aerospace Recommended Practice
AS	Aerospace Standard
ASC	Aircraft System Controller
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
ATCS	Advanced Technology Crew Station
ATIS	Automatic Terminal Information Service
BITE	Built-In Test Equipment
CAA	Civil Aviation Authority
CAD	Computer Aided Design
CALSEL	Call Select
CBI	Computer Based Instruction
CDU	Control Display Unit
CE	Certification Engineer
CFR	Code of Federal Regulations
cm	Centimeter
CMOS	Complementary Metal Oxide Semiconductor
CMU	Computer Mock-Up
COMBIMAN	Computerized Biomechanical Man-model
C _p	Pixel Capacitance
CPU	Central Processing Unit
CRM	Cockpit Resource Management (also Crew Resource Management)
CRT	Cathode Ray Tube
CSERIAC	Crew System Ergonomics Information Analysis Center
dc	Direct current
DEP	Design Eye Position
DME	Distance Measuring Equipment
DoD	Department of Defense
DyF ₃	Dysprosium Fluoride
EADI	Electronic Attitude Director Indicator

Ec-	Negative-Expressive
EFIS	Electronic Flight Instrument System
E_g	Energy gap
EIA	Electronic Industries Association
EL	Electroluminescent
ELS	Electronic Library System
EVS	Enhanced Vision System
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FAS	Flight Deck Alerting System
FCC	Flight Control Computer
FDI	Flight Director Indicator
FET	Field Effect Transistor
FMA	Flight Mode Annunciator
FMC	Flight Management Computer
FMS	Flight Management System
FOV	Field of View
fL	foot-Lamberts
g1	Grid 1
g2	Grid 2
g3	Grid 3
g4	Grid 4
GaAs	Gallium Arsenide
GaAsP	Gallium Arsenide Phosphide
GaP	Gallium Phosphide
HDD	Head-Down Display
HF	High Frequency
Hg	Mercury
HIRF	High Intensity Radiated Fields
HLD	Head-Level Display
HMD	Helmet Mounted Displays
HMS	Helmet Mounted Sight
HSI	Horizontal Situation Indicator
HUD	Head-Up Display
Hz	Hertz
I-	Negative-Instrumental
IC	Integrated Circuit
IE+	Instrumental-Expressive
I_f	Forward Current
IFF	Identification Friend or Foe
ILS	Instrument Landing System
INS	Inertial Navigation Systems
IR	Infrared
IRS	Inertial Reference System

ITO	Indium Tin Oxide
ITS	Intelligent Tutoring System
kHz	Kilohertz
LC	Liquid Crystal
LCS	Liquid Crystal Shutter
LED	Light Emitting Diode
LOFT	Line Oriented Flight Training
LRRA	Low Range Radio Altimeter
LRU	Line Replaceable Unit
LSI	Large Scale Integration
MCDU	Multi-Purpose Control Display Unit
MTK	Multi-Function Keyboard
MKR	Markers
MLS	Microwave Landing System
mm	Millimeter
Mn	Manganese
N	Nitrogen
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
ND	Navigation Display
NTSB	National Transportation Safety Board
NVG	Night Vision Goggles
PA	Public Address
PAI	Primary Attitude Instrument
PFD	Primary Flight Display
PNF	Pilot Not Flying
PNI	Primary Navigation Instrument
PrF ₃	Praseodymium Fluoride
PVI	Pilot-Vehicle Interface
R _c	Column Pixel Resistance
RCP	Reconfigurable Cockpit
R _L	Load Resistor
ROM	Read-Only-Memory
R _r	Row Pixel Resistance
RTCA	Radio Technical Commission for Aeronautics (now known as Requirements and Technical Concepts for Aviation)
SAE	Society of Automotive Engineers (now known as Engineering Society for Advancing Mobility Land Sea Air and Space)
SAE TSB	Society of Automotive Engineers Technical Standards Board
SATCOM	Satellite Communications
SATNAV	Satellite Navigation
SD	System Display
SELCAL	Select Call
SOP	Standard Operating Procedure

STN	Supertwisted Nematic
TACAN	Tactical Air Navigation
TbF ₃	Terbium Fluoride
TDZE	Touch Down Zone Elevation
TFEL	Thin-Film Electroluminescence
TFT	Thin-Film Transistor
TmF ₃	Thulium Fluoride
TN	Twisted Nematic
TSO	Technical Standard Orders
TTL	Transistor-Transistor Logic
UHF	Ultra High Frequency
UL	Underwriter's Laboratory
UV	Ultra-Violet
V	Volt
V _B	Breakdown Voltage
V _{CC}	Collector Circuit Voltage
V _F	Forward Voltage
VFD	Vacuum Florescent Display
VHF	Very High Frequency
VLF	Very Low Frequency
VOR	Very High Frequency Omnidirectional Range
V _s	Sustain-Voltage
Zn	Zinc
ZnS	Zinc Sulfide
ZnSe	Zinc Selenide